IDENTIFYING THE RELATIONSHIP BETWEEN DAYLIGHTING DESIGN, OCCUPANT SATISFACTION, AND PERCEIVED PERFORMANCE

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ABSTRACT

There is a lot of excitement over the idea of “going green” when it comes to buildings because it is associated with energy savings and a reduced environmental footprint. Daylighting, or lighting interior spaces via natural light, is one such strategy already receiving attention from designers, but without a fuller understanding and sounder implementation strategies daylighting might not be optimized and worse, may pose a hindrance to occupants. This study puts the spotlight on the occupant as it examines the usefulness of daylighting and investigates the impact daylighting has on occupant comfort, satisfaction, and perceived performance. It also investigates what features of a specific daylighting design strategy have the greatest impacts. The methodology for this study includes the creation and usage of a daylighting design evaluation toolkit comprised of an occupant visual environment survey, lumen meter, fisheye lens camera, and glare-identifying computer software. Seventy-five occupants from a university laboratory building participated. Results showed that occupants in daylit spaces are more satisfied with their work environment, although conclusions regarding perceived performance could not be made. Exterior horizontal shading was found to have the strongest association to higher comfort and satisfaction ratings. Small scale fixed exterior vertical shading was actually found to have a negative correlation to occupant comfort and satisfaction, although this may be due to the specific vertical shading design. Further exploration with the data revealed that occupants who had glare in their workspace glare did not report dissatisfaction with it, but those with veiling reflections from electric light sources did report significant dissatisfaction. Additionally, occupants with controls over their electric lights showed greater satisfaction with the amount of light at their workstations.

BIOGRAPHICAL SKETCH

Anne Oswald was born in Steubenville, Ohio and moved to Rochester, New York with her family at age seven. She received her elementary education in the Rochester City School District at Charles Carroll School #46 before moving to Penfield, N.Y. for both her middle and high school education. She graduated salutatorian with a Regents Diploma with Honors in 2004.

After high school, Anne came to Cornell University to study Human Development, though after taking a couple classes in the Design and Environmental Analysis program she switched majors selecting the Facility Planning and Management option. Over summer breaks Anne interned with the General Services Administration in Washington, D.C. and T. Rowe Price's Facility Planning and Design Department in Baltimore, M.D. She earned a Bachelor of Science Degree with Distinction in May 2008 and matriculated to the Master's of Science program that fall.

Anne served as the Vice President of the Cornell Chapter of the International Facility Management Association for the 2007-2008 year before serving as its President during her year as a graduate student. She was able to attend IFMA's annual conference, World Workplace, in both 2007 and 2008 as a scholarship recipient. Upon completion of her Master's degree Anne accepted a position with Raymond James Financial as a strategic occupancy planner at their headquarters in St. Petersburg, Florida.

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CHAPTER 1

INTRODUCTION

Effects of lighting on productivity garnered interest nearly a century ago when Western Electric hired specialists from Harvard to come study their factory workers. Regarding productivity and lighting, no conclusive relationship was actually identified, but instead the world discovered the Hawthorne Effect.

Today, with green building on the rise, *day*lighting's effect on the built environment and its occupants attract the attention of environmental psychologists, engineers, and designers. With talk and excitement mounting each day over sustainable buildings and "going green" the case is often made to incorporate daylighting because of its impact on energy bills. However, architects and building owners run the risk of failing the occupants if they do not incorporate daylighting in a wise manner as it is known that glare can be a large impediment to a successful workforce. Furthermore, the energy savings may never be realized if a sloppy design allows heat to enter in the summer and flee to the outside in the winter. If poor designs spread then daylighting could find itself with a poor reputation and an opportunity will have been lost because on the other hand, when daylighting strategies are well designed and integrated with the design of other building systems, it is suspected that the financial benefits do not stop at energy savings but carry over to even larger gains in the form of happier, healthier, higher performing occupants.

Developing and using a daylighting design evaluation toolkit, this study looks to the relationship of daylighting design and occupant comfort, satisfaction, and perceived performance in an academic laboratory setting to discover the usefulness of daylighting to occupants.

CHAPTER 2

LITERATURE REVIEW

2.1 Daylighting Impact on Occupant & Building

Our understanding of the relationship between daylighting and human beings has evolved over decades of research sought out through both individual and industrial motivations, and often guided by collective observations. For as long as humans have walked the earth we have been aware to some capacity the role natural light plays in our lives. People on average are in better moods when in sunlight (Lambert *et al*. 2002). Research has gone further to better understand this relationship discovering, among other findings, the effects of natural light on our circadian rhythms. Still it is not fully known how far-reaching the effects of natural light are on humans. Now with the "green" revolution about to take off and daylighting's imminent greater utilization, besides the understanding of how to harness the solar power to illuminate indoor space, it is important to understand the impact of daylighting design strategies on occupants to ensure its use is optimized and not harmful.

2.1.1 Comfort

Comfort, specifically environmental comfort, is a broad ranging term laced with subjectivity and comprised of a multitude of facets including temperature, humidity, aesthetics, ventilation, and lighting. There is an ever-broadening body of research aimed at better understanding the impact of these different facets on occupant comfort. For the purposes of this study the term comfort was limited to the contexts of visual comfort as pertaining to artificial versus natural lighting, however research over time has proven it difficult to always separate the facets of comfort as many are interrelated, with thermal comfort being a notably intertwined one (Paul & Taylor, 2008). A complex topic indeed, lighting comfort is made up of both visual factors such as amount and source of light, its spectral distribution, color rendition, glare, and non-visual factors such as the biological, physiological, and behavioral aspects of people (Abdou, 1997).

Humans have a general preference for daylighting over artificial light sources. As the most natural light source, daylight is what humans have come to consider and compare all other lights sources to (Robbins, 1986; Franta & Anstead, 1994). This preference may come from biological predispositions. Sunlight provides a balanced color spectrum and has a slight energy peak in the blue-green portion of the visible spectrum (Liberman, 1991). This spectral character of sunlight has an immense effect on the human body's photochemistry and spurs physiological and biochemical responses (Maclaughlin *et al.*, 1982). Research on light's physical effects on humans is well developed and the argument can rather easily be made that as humans evolved under the sun we developed a facultative symbiotic relationship with it.

Comfort has a psychological aspect to it as well. Heerwagen and Heerwagen (1986) surveyed office workers in Seattle and found that a majority felt daylight was better for their psychological comfort. What's more, daylight has also been found to create a greater sense of spaciousness in rooms, generally considered to be a factor of comfort. Inui and Miyata (1973) asked 10 participants to rate 474 models of rooms on various criteria including spaciousness and found that perceived spaciousness was greatest in the rooms with large windows or large volume. The rooms that were rated more spacious were rated more pleasurable as well.

Ergonomics and human factors play a role in natural light providing greater comfort as well. In addition to improved mood, enhanced morale, and lower fatigue, reduced eyestrain has all been associated with daylighting (Edwards & Torcellini, 2002). When appropriately located, windows provide ideal eye-task-lighting geometries for reflective visual tasks, which would occur when not using self-luminous displays, such as computer screens (Bayer *et al*., 2006).

With the overwhelming preference for daylight comes a degree of aversion to artificial lighting. In an early study on office daylighting by Markus (1967), 96% of those surveyed preferred to work under natural light rather than electric light. Similarly, in a questionnaire distributed to a large British company, 69% of 295 participating employees felt that electric light was not as good as daylight. In the same study, when asked to choose where they would want to place their desk in a model of the building, 81% chose a position near a window (Manning, 1965). Cuttle (1983) confirmed this in a study of English and New Zealand office occupants where she found four out of five preferred working in daylight because they felt discomfort working by electric light. Specifically, the employees believed that it was more the short-term discomfort causing their concern rather than any long-term negative effects.

No discussion on daylighting and comfort is complete without consideration given to two secondary effects of most daylighting sources: exterior views and glare. Glare is non-uniform spatial distribution of luminance. Glare has also been defined as brightness "sufficiently greater than …[that] to which the eyes are adapted to cause annoyance, discomfort, or loss in visual performance and visibility" (McCormick, 1976). It has been attributed to the variation between task and surround luminance, veiling reflections, and shadows (Abdou, 1997). It is important to note the two different types of glare as it relates to effects on the occupants: disability glare and discomfort glare. On one hand, disability glare, resulting from an overly bright source in the line of sight such as the sun, a luminaire, or an excessively reflective surface, reduces the visibility of objects through a blinding effect, but does not always cause discomfort. On the other hand, discomfort glare may not necessarily reduce visibility, but instead cause fatigue through excessive contrast ratios (Cakir, *et al*., 1980).

Typically in interior settings it is discomfort glare from the contrast between task and luminaires or windows within visual ranges that occupants experience (Abdou, 1997).

In developing a Daylighting Glare Index, Hopkinson (1970) asked participants to make judgments about discomfort in various glare conditions. He discovered that people were more tolerant of glare originating from daylight than of glare originating from non-daylight sources. A frequent comment received from participants divulged that the view outside the window influenced the judgment of glare leading to the supposition that a pleasant view can buffer the impact of glare. Very similarly, in a survey of nine daylit buildings in the United States and Germany, Osterhaus (2001) found in offices with either an east or west orientation that glare was less of a problem or even was ignored if a pleasant view as available. The conclusion followed that providing access to a view was more important than any possibility of introducing any perceived discomfort glare from the windows.

The view a window provides is undoubtedly a contributing factor to the comfort that natural light provides. In fact, the very factor of 'a view' has made attempts at predictions of discomfort relating to glare unsuccessful in widespread application (Hopkinson, 1972). Accordingly, in a survey of 1,823 Danish office workers, the most positive aspect of a window was found to be "a view out" (Christoffersen *et al*., 2000). The ability to see the weather outside was rated the second most positive feature. Similarly, in the survey of British officer workers mentioned earlier, Manning (1965) reported that 88% of the 2,500 participants remarked that it was "important to be able to see out of an office" giving greater credence to the importance that windows holds for occupants.

Recognizing that daylighting preferences are very subjective, a study was conducted through an online questionnaire to students at the Hong Kong Polytechnic University. It asked participants to rank illustrations of similar-looking rooms based on their own preferences. Each room had a different combination of levels of the following attributes: general brightness (bright/dim), desktop brightness (bright/dim), perceived glare (often/rarely), sunlight penetration (often/rarely), quality of view (good/bad), user friendliness of shading control (easy/difficult), and impact on energy saving (save/waste). It was found through conjoint analysis that quality of view was the most important attribute of the ones sampled in determining a preference for a particular room (Cheung & Chung, 2008).

Not only does a window provide a view through, but also an opportunity to relax. A far off view provides eye muscles a chance to relax thus avoiding eyestrain due to a more distant focal point (Vischer, 1989). Furthermore, views can be effective in reducing stress. Ulrich (1981) found that viewing natural views containing vegetation or water reduced stress levels and decreased anxiety.

Clearly, glare and views are key factors in understanding the comfort provided by natural daylight. Still though, not all research has necessarily found a positive link between comfort and green building in general. In a study of two university buildings in Australia, one “green” and one “conventional,” occupant perceptions of comfort and satisfaction were probed using a 7 point semantic differential scale with questions about lighting as well as humidity, temperature, ventilation, acoustics, aesthetics, and serenity. No significant differences between the two group’s comfort or satisfaction levels were found when controlled for a malfunctioning cooling system (Paul & Taylor, 2008). However, this study was limited in its assessment of visual comfort perceptions using only a scale of ‘too sunny’ to ‘not enough sun’ and did not measure if the ‘green’ building did indeed provide more daylighting than the other.

2.1.2 Satisfaction

Interestingly, the research between daylight and satisfaction is much more straightforward, much less complicated, and seemingly subject to fewer contributing variables than that on comfort. The research on satisfaction with daylighting shows a conclusive link with higher job satisfaction.

Theories on job satisfaction's connection to the physical environment assert that employees will not take into account their workplace environment if it is adequate when rating their job satisfaction. However, job satisfaction *will* suffer in instances where the environment is uncomfortable or harsh (Sundstrom and Sundstrom, 1986). Along these lines, quite a few studies have found that employees in windowless buildings have substantially lower job satisfaction and are overall less positive than other employees who have windows in their workspaces (Collins, 1975; Finnegan and Solomon, 1981). Ruys (1970) found that 90% of female workers in windowless offices in Seattle were dissatisfied with their offices to the point of disliking their offices. They cited no daylight, inability to know the weather, and inability to see out and have a view as reasons for their dissatisfaction. Research on windowless office spaces by Boyce (2003) establishes that job dissatisfaction and dissatisfaction with the physical environment increase for occupants in rooms that give little opportunity for relief and stimulation.

Inversely, several studies have found higher job satisfaction among employees working under daylight. In a study on 100 white and blue-collar employees at a winemaking company in Southern Europe the amount of sunlight penetration was found to significantly correlate in a positive direction with job satisfaction, better well-being, and a lower intention to quit (Leather *et al*., 1998). Similarly, after undergoing a renovation at its Costa Mesa, C.A. campus in which a "comprehensive daylighting strategy" was incorporated, Verifone employees' post-occupancy comments included “in my previous office, it felt cooped in, always artificially lit…but here, if I look up, I can see glimpses of the sky outside and that makes me feel good” and also “working in this building is like working outdoors- the light streaming into my workstation is wonderful” (Sundaram & Croxton, 1998). These anecdotes are powerful in suggesting daylighting positively impacts employees’ satisfaction levels with their workplace.

One indication of greater satisfaction with daylight was found in a study of Canadian office workers. While researching user behavior regarding electric light switches, Love (1998) found that in 80% of the cases office occupants would wait until daylight illuminance was between 210 and 380 lux before turning on a light and in fact in 50% of the cases occupants tolerated 150-260 lux before turning on a light. These illuminance levels are much lower than what is usually required from electric lighting and therefore possibly indicative of a greater contentment with daylight.

2.1.3. Performance

Just as it is understood that humans were not meant to sit still in chairs for eight hours a day, it has also been asserted that we were not meant to spend our lives inside and therefore may not function at our physiological or psychological best when kept in artificial environments for long periods of time. This speculation has led to a large body of research regarding performance and lighting dating back to the famous Hawthorne Experiments between 1924 and 1933 when the Western Electric Company decided to investigate the relationship between quality and quantity of illumination and employee performance (Sundstrom & Sundstrom, 1986). While the Hawthorne Experiments were inconclusive regarding the effects of illumination on occupants (and instead uncovered what we know today as the Hawthorne Effect), our greater understanding today of the relationship between lighting and comfort and satisfaction can better help us advance what we know about the lighting-performance link.

Productivity is most often the "go-to" measure of performance as it encompasses accuracy, speed, and overall efficiency. This is usually most applicable in industrial settings, such as the Western Electric Hawthorne plant, where it is the easiest to measure. In educational, retail, and office environments, environments where daylighting research has also since been conducted, productivity is more difficult to measure and a generalized formula looking at inputs and outputs is less applicable. Instead, very often, productivity is assessed with self-report techniques.

Again, although a hiatus was taken after the disappointing findings of the Hawthorne studies, decades of research have since been conducted regarding the effect of light on performance, starting with looking at the quantity of light in general. Naturally, since nearly all tasks require the ability to see and thus require some amount of lighting indoors a lot of earlier research was aimed at identifying the ideal range to determine the minimum and maximum light levels to ensure best performance. One early study in particular (Stenzel, 1962) suggested that the amount of light may be more important than the source of light. This study examined the performance of employees stamping shapes for leather handbags. At first employees worked with a total illuminance of only 350 lux provided by localized fluorescent light which was a supplement to the natural daylighting present, but after two years daylighting was eliminated and general fluorescent lighting was used to provide a more uniform illuminance of 1000 lux. For the next two years while measurements were taken of twelve employees present for the entire four years, an average performance increase of 7.6% was found. Here though it is not clear what aspect of the lighting caused the performance boost – the change in source, distribution, or illuminance – as all three are possible culprits.

In general, most early research has found though that, up to a point, increased lighting increases productivity (Fisk, 2000). A study of employees at an insurance company performing complex paper-based tasks found that productivity increased nearly 3% when illumination increased from 500 lux to 1100 lux. Furthermore, when illumination rose to 1600 lux, productivity increased an additional 8% (Barnaby, 1980). Boyce (1973) evaluated the effect of various illumination levels between 20 and 150 footcandles on a visual performance task – Landolt ring charts – and found that for participants 16 to 30 years old the effects of added illumination were minimal. However, the effects were significant for those aged 46-60. Not surprisingly, higher illumination levels can have a greater benefit to older workers (Sundstrom & Sundstrom, 1986).

More specific to daylighting illuminance levels, another study found that output from an English linen weaving factory followed daylight intensity levels whereby production decreased markedly as daylighting levels decreased (Sundstrom & Sundstrom, 1986). This task required high amounts of visual discrimination which was not provided at times in the later afternoon when daylight decreased to as low as 2 footcandles.

However, not all studies have found a link between performance and increased illumination. Several studies evaluating tasks such as proofreading accuracy, reading speed and reading comprehension have not shown statistically significant effects of illumination (Fisk, 2000). Finally though, no research has shown that increased illuminance decreases performance and very few show that decreased illuminance increases performance (NEMA, 1989).

Still after decades of research, there is not quite total consensus regarding optimum lighting levels. Looking at the Illuminating Engineering Society's own guidelines over the past six decades reveals a very inconsistent track record of recommendations ranging from as low as 200 lux to as high as 1000 lux for regular tasks and from as low as 500 lux to as high as 2000 lux for difficult tasks (Boyce, 1995). Boyce (1995) put it best when he described the possibility of discovering a "magic formula" for illuminance levels as a "fairy tale." As he explained, since every task has not only a visual, but also a motor and cognitive component, finding a formula to cover all the possible unique combinations of the three is impossible.

Unlike industrial or manufacturing settings, research on performance in office environments heavily relies on self-report data. However, self-assessment data of productivity is commonly considered reliable (Thompson & Jonas, 2008), especially when measured in a comparative manner to assess change initiatives (Leaman, 1999). In a post-occupancy evaluation of the first LEED Platinum building, the Philip Merrill Environmental Center in Annapolis, Maryland, the Indoor Environmental Quality Survey developed by the Center for the Built Environment at U.C. Berkeley was administered to 71 of the 92 occupants. Through this self-report survey, it was found that occupants rated the improved lighting conditions (most notable was the daylighting) as enhancing their ability to work by 74% (Heerwagen & Zagreus, 2005). Additionally, Veitch and Gifford (1996) in a survey of office workers and university students in Canada found 52% of the sample reporting that they "did their best work when in places lit by natural light."

Lockheed Martin has also benefitted from implementing daylighting in its Building 157, built in 1983, in Sunnyvale, California. The 600,000 square foot office building was designed with 15-foot high window walls and sloped ceilings for deeper penetration and a large central atrium allowing daylight to provide nearly all of the ambient light. Although daylighting was not the only new feature (noise dampening technologies were implemented along with more flexible and reconfigurable workstations), productivity was reportedly 15% higher on the first new contract awarded to the building and daylighting has largely been credited for this gain (Romm, 1999). Similarly, an American insurance company headquartered in Wisconsin, incorporated extensive daylighting as well as other system upgrades into its 150,000-square-foot office building and saw a 16% increase in worker productivity through the number of claims processed (Kroner *et al*., 1992; Romm & Browning, 1994). Personal control workstations were found to be responsible for 3% of this productivity gain while the remaining 13% gain is likely due to many factors of which daylighting is one; 92% of employees had workstations near the window wall in the new building as compared to only 30% in the old building (Heerwagen, 2000).

Perhaps one of the most conclusive finding about productivity and windowed environments are the associated lowered rates of absenteeism because it goes without saying that people are more productive when they are at work (NEMA, 1989). Lowered absenteeism rates are widespread among companies implementing daylighting. In the new Verifone campus building mentioned earlier, which featured a "comprehensive daylighting strategy" including skylighting, absenteeism rates fell 40% as compared to other Verifone buildings right next door performing the same jobs. This was in addition to a reported 5% increase in productivity (Sundaram & Croxton, 1998; Romm, 1999). Furthermore, after completing building upgrades to use more daylight, Pennsylvania Power & Light reported absenteeism rates dropped 25 percent (Allen, 1982). And the benefits of reduced absenteeism have long been known. Robbins (1986) states "reduced sickness and absenteeism … would more than offset any increased first costs or life cycle costs."

It must be noted though that the effects of daylighting and those of exterior views on productivity are hard to separate from each other, except possibly of course with the use of skylights. However, two different studies on a utility company call center and office area had success in separating the two variables using a variety of complex statistical models. The models were capable of determining if any of the variations in office environmental conditions, of which views and daylight illumination were included, were significantly associated with occupant performance. Performance in the call center was rated by average length of call and performance in the offices was scored based on a variety of short mental tasks performed at their personal workspace computer. Several significant ($p<0.10$) correlations were found including one between view and performance. Workers in the call center with a better view (determined by size of window and amount of vegetation) processed calls between 6-12% faster than workers with no view, while workers in the office area with the best views performed 10-25% better. On the other hand, daylight illumination levels showed an inconsistent relationship with performance only correlating positively with one of the computer tasks and actually correlating negatively with average length of call in the call center in one of the two time periods studied. However, it was found that the natural log of daylight illumination levels had the best fit to the data, which implies greater sensitivity to illumination changes at lower levels and increasingly less sensitivity at higher levels (Heschong Mahone Group, 2003a).

Along with the possibly confounding variable that is an exterior view, glare is relevant to the discussion on performance as well. While these by-products of daylighting affect occupant comfort levels, it's no surprise that they also relate to occupant performance. In the same study of office worker performance on mental tasks on desktop computers it was found that the glare potential from windows had a significant negative impact on performance in three of the five tests where the greater the glare potential from primary view windows, the worse the office worker performance, decreasing by 15% to 21% with all other factors being equal (Heschong Mahone Group, 2003a). Similarly, in a study reported by Allen (1982) after undergoing a lighting upgrade which reduced the veiling reflections in the building and actually decreased the illuminance slightly, the company experienced a 13% increase in productivity of the drafting team where the average time for a drawing decreased from 6.93 hours to 6.15 hours. However, Sundstrom & Sundstrom (1986) note that while glare may negatively impact job performance it has more often been connected with job dissatisfaction.

Two more studies worth noting have looked at the effects of daylighting in retail environments. In a study of a large retail chain, of which approximately two-thirds of the 108 stores had skylights and the remaining third did not, it was found through a multivariate regression analysis that after controlling for square footage, hours of operation, location, date of original construction and most recent renovation, average household income in the area, and population the stores with the skylights benefitted from 40% higher sales with a range between 31% to 49%. The daylit and non-daylit stores were nearly identical with the same layout, facades, signage, accessibility and even artificial lighting as "quality lighting design is very clearly considered part of the merchandising strategy for the chain" (Heschong Mahone Group, 1999a). A couple years later in a follow up study on another chain of stores from a different retail sector (73 stores of which 24 had some daylighting) a dose response relationship was found between sales volume and the number of hours of daylight per year that exceeded the illumination provided by the electric lights. However this relationship was of a lesser magnitude than in the earlier retail study – 6% compared to 40% higher sales – and is possibly due to the fact that the second retailer did not have nearly as an aggressive daylighting strategy implemented (Heschong Mahone Group, 2003b). Still though, daylighting had an equal amount of explanatory power in predicting retail sales as other traditional predictors such as number of competitors or parking lot size.

In a less formal study of a prototype Wal-Mart store called "Eco-Mart" in Lawrence, Kansas it was discovered through real time register activity that the sales per square foot of the one half of the store where skylights had been installed were "significantly higher" as compared to the departments not located under the skylights. Furthermore, sales in these daylit departments were even higher than for the same departments located in other stores (Romm & Browning, 1994). While skylights had been intended for the entire "Eco Mart" store, cost cutting measures eliminated them from roughly half the store and this allowed for a mini experiment whereby products from the daylit sections were swapped with products not normally located under the skylights. Again it was found that the products under the skylights had significantly higher sales, while the products no longer under the skylights saw their sales levels return to their national sales average (Good, 1999; Pierson, 1995). Even more interestingly, while no data has been collected on this, it has been reported anecdotally that after installing the skylights clothing returns have decreased dramatically (Heschong Mahone Group, 1999a).

Unlike big box retail environments, daylighting strategies once came standard in schools, but with the advent of air conditioning in the 1960s building engineers objected to the then-conventional large windows and high ceilings and building codes dropped daylight illumination requirements in favor of inexpensive fluorescent lighting (Heschong, 2002). Today though educational environments have become another setting to draw interest on the effects of daylighting on performance as new technologies have made daylighting practical once again and test scores have allowed for a more quantitative assessment. Accordingly, in a large and well-designed study of an elementary school district in San Juan, California it was found that the reading and math test scores of second to fifth grade students in classrooms with the most overall daylighting improved 26% and 20% respectively on standardized tests over a one-year period as compared to students in classrooms with the least amount of overall daylighting. In this study, classrooms were assigned a series of codes on a 0-5 scale based on their size and tint of windows, presence and type of skylighting, and overall quality and quantity of daylight expected. The regression equation also controlled for 50 other variables such as socio-economic status and special programs. Study results also found that in the classrooms with skylights that diffused the daylight throughout the room, and which teachers could manually control, students improved 19-20% faster than students not in controllable skylit classrooms (Heschong Mahone Group, 1999b). To confirm that the improvement was not due to better quality teachers in the daylit rooms a re-analysis report was conducted, which conclusively found no assignment bias (Heschong Mahone Group, 2001).

A follow up study in 2003 was also conducted, this time in Fresno, California. Researchers looked at the test scores of eight thousand 3rd – 6th grade students in over 450 classrooms which were measured and assigned an overall daylight code similar to the 1999 study. However, the findings relating the daylight code to student performance could not be replicated, i.e. the code was not significant in predicting student performance in Fresno as it had been in San Juan. In light of this, using multi-linear regression analyses a multitude of variables were tested to see which individual variables might best explain student performance and it was found that quality of view positively correlated ($p < 0.10$) with reading and math test scores showing between a 6-14% increase. Conversely, glare and lack of control over window curtains or blinds were found to negatively correlate ($p < 0.05$) with student performance with a 5% and 7% decrease respectively (Heschong Mahone Group, 2003c).

In addition, in Johnston County, North Carolina a much less statistically rigorous study compared the performance of students on standardized tests from both non-daylit and three newly constructed daylit schools. The daylit schools used many daylighting strategies such as south facing roof monitors, translucent fabric baffles, light sensors, and shades. The study found that students in the daylit schools outperformed their peers by 5 to 14% in the short-term or long-term respectively. It is important to note that these gains were not necessarily due to the fact the daylit schools were new because the middle school was also newly constructed without daylighting and saw a negative impact on its students' performance (Nicklas & Bailey, 1997; Romm, 1999).

Test scores are not the only metric through which to assess daylighting's effect in schools. A study of 88 eight-year old students in four classrooms in Sweden, of which two classrooms had daylighting and two had no daylighting, found significant correlations between not only daylight and hormone levels, but also student behavior. Over a one-year period the two groups of students were observed and their cortisol (a stress hormone governed by the body's biological clock) levels were measured. It was concluded that classrooms without windows may upset basic hormone functions thus influencing children's ability to concentrate and cooperate as well as negatively impact annual body growth and sick leave (Küller & Lindsten, 1992).

This collective research on schools and daylighting has prompted the following conclusion by Heschong: the "consistency across such diverse school environments persuasively argues that there is a valid and predictable effect of daylighting on student performance or that some other unidentified factor consistently linked with daylighting improves student performance" (Heschong, 2002, p. 67). Rather similarly, having been tasked with reviewing all evidence regarding effects of green school design, of which natural lighting is a key component, the National Academy of Sciences literature review for MASSTECH concludes "there is value in attempting to identify design features that may lead to improvements in learning, health, and productivity for students, teachers, and other school staff, even if empirical results are less than robust" (Bayer *et al*., 2006).

So while the more recent studies seem to trumpet the positive effects of windows in classrooms it is important to note that they contradict earlier studies, which, while less statistically rigorous, did not find as conclusive results. Demos *et al*. (1967) conducted a two-year study on fifth grade students in windowed and windowless classrooms in Palm Springs, C.A. comparing grade averages, achievement test scores, health records, and personality tests and found no significant differences between the student classes. Additionally, opinions of the windowless classroom among the affected students were inconsistent changing from the first year when they reported liking it to the second year when they disliked it. However, teachers who were interviewed noticed that students in windowless classrooms complained more. Similarly, Larson (1965) found no difference in academic performance during the course of a three-year study of elementary school children where windows were present in the classroom for years one and three, but were removed during the second year.

It is almost always the case that the productivity gains trump any other savings and provide the best argument for implementing relatively more expensive upgrades such as daylighting because the return on investment is so fast and large in this regard (Romm & Browning, 1994). Whether it is through improved test scores, fewer errors in manufacturing, higher sales volumes, or healthier and less absent employees the evidence is starting to mount that daylighting can contribute to better occupant performance.

2.2 Criteria for Good Daylighting Design

As daylighting has surged and waned in its use in the building and architectural industries over the past century, research and technologies have kept up to allow for smart, strategic, and whole-building approaches to lighting buildings with daylight. Still though, it was only twenty years ago when the following observation was made: "Even today windows are generally discounted by designers as sources of light, mainly because the amount of light they supply is unpredictable owing to varying weather conditions. In fact it is customary for lighting engineers to specify lighting for office interiors that ignores the amount of light provided by windows" (Vischer, 1989). Recognizing the benefits to not only energy savings, but also to the occupants, daylighting strategies can be successfully implemented in order to supplement if not replace artificial lighting. The following sections examine what is known today in terms of creating good daylighting design.

2.2.1 Building depth and floorplate shape

Decisions about the building depth and the foorplate shape of the building are not often the first to be made with regards to the construction of a new building, but they are some of the larger, if not the two largest, determinants impacting all other daylighting design decisions for a building. If the goal is to maximize the occupants' access to daylight, then a narrow floorplan is the obvious winner. Deep buildings with conventional windows restrict daylighting to the perimeter, while articulated floorplates allow for a greater percentage of perimeter walls and thus greater exposures and levels of access to daylighting. Furthermore, daylight from a side window in a room with normal ceiling height cannot provide adequate daylight to spaces farther than 15 feet from the window and thus shallow private offices are recommended (O'Connor *et al.*, 1997). Of course just as there are visual tradeoffs with introducing daylighting (e.g. glare), there can be thermal tradeoffs when the proportion of perimeter walls is increased and so careful planning with other building systems must be taken (Ander, 2003).

2.2.2 Penetration strategies

When land restrictions do not permit narrow building plans, and deep buildings are the most feasible, daylight does not necessarily need to be limited to the windowed perimeter spaces. While the general rule of thumb is that daylight penetrates only about two and a half times the height of the window (Robbins, 1986; Ander, 2003; Kwok & Grondzik, 2007; Whole Building Design Guide, 2009), daylight can still be brought into the interior spaces through a variety of strategies.

Atrium spaces and lightwells are possible methods for bringing daylight into otherwise interior spaces by essentially creating a second perimeter zone within the building core around which interior offices or workspaces can be wrapped. These spaces are thus able to benefit from daylight that has been reflected. Atria are highly successful in admitting daylight because they reach the sky dome at its brightest point overhead. It is important to keep in mind the aspect ratio of an atrium, as smaller amounts of daylight will reach the lower levels in a tall and narrow atrium. One possible way, however, to maximize the sky view at the lower levels is to set back the floor plans of the higher levels although this has economic limitations (Phillips, 2004).

Light shelves are another way to introduce daylight deeper into interior spaces. Exterior light shelves reflect light into the building, while interior shelves take the light and send it deeper often by reflecting the light off the ceiling. When designed appropriately, a system of interior and exterior light shelves can increase a room's brightness while simultaneously decreasing the window brightness by reducing the light's intensity and partially absorbing it (Ander, 2003). Light shelves are most effective on south-facing facades, although they can sometimes work on east and west facades (O'Connor *et al*., 1997).

Clerestories (windows whose sill height is above eye level but below ceiling height) also allow for daylight penetration into interior spaces such as offices or corridors. Similar to light shelves, clerestories result in a greater distribution of brightness thus reducing glare potential. Furthermore, because a view through them is not necessary due to their height, clerestories offer greater flexibility in their glazing choices.

Lastly through new optical technologies, light can be brought into the core spaces of a building through either active or passive daylighting tracking systems, which have collection, transportation, and distribution system components (Ander, 2003). As is most often the case, the best results with any of these strategies are seen when they are implemented during the design phase, as a multitude of factors need to be considered and dealt with.

2.2.3 Location of Windows: Sidelighting vs. Toplighting

The location of conventional side windows can be another strategy to increase the depth of daylighting penetration as well. Locating the aperture higher above the finished floor will result in a deeper penetration of daylight and as the windowsill height rises the point of greatest illumination will move farther away from the window wall. Furthermore, the higher the window is, the lower the likelihood of excessive brightness in the field of view because the light will be more scattered before reaching task level (Ander, 2003). Ceiling height also plays a role in this discussion on daylighting because as window heights stretch closer to the ceiling they can allow admitted daylight to reflect off the ceiling plane and push deeper into the space.

Arguably one of the primary benefits of sidelighting is the added view. Due to the fact that occupants cite the view as often one of the best features of a window and research has linked a higher tolerance for glare to a better view from a window (Osterhaus, 2005), the view out a window should be considered when locating such apertures. However still, a primary disadvantage of daylighting in general is glare and this is certainly the case with sidelighting as there is the potential for great contrast between the aperture and the surrounding wall surfaces (Ander, 2003). Besides turning to shading strategies which can largely mitigate the glare liability (discussed later), there are two recommendations available for minimizing glare from sidelighting sources. The first is to utilize strip windows rather than punched windows in order to altogether eliminate the contrast in brightness between the aperture and surrounding walls (O'Connor *et al*., 1997). The second recommendation is to separate windows for light from windows for view. This allows windows providing a view to have a lower visible transmittance rating, which can reduce the glare potential, because a second set of windows above will be responsible for letting in daylight with completely clear glazing (BetterBricks, 2009).

Daylight cannot only be brought into a building through conventional sidelighting sources such as windows, but also through apertures above the ceiling line. Toplighting can be very effective, although very different from sidelighting in its distribution of daylight as well as its restriction to lighting only upper floors. Skylights, which are one of the most common types, are able to introduce large amounts of light from the zenith – the brightest part of the sky – but they do introduce the risk of discomfort from direct beam sunlight. Therefore, small, closely spaced skylights are preferable to large widely spaced ones to ensure a more even distribution of light and greater energy savings (Ander, 2003). Daylighting tracking and reflecting systems can be implemented with skylights to increase the daylighting potential by following the sun's path throughout the day mechanically or with mirrors and better directing the sunlight into the spaces below. Lastly, roof monitors, such as sawtooth roof constructions, are another option for toplighting offering more angled apertures capable of reducing solar heat gain. These however do require greater coordination with the roof architecture (Kwok & Grondzik, 2007). No matter the chosen toplighting strategy it is imperative that it include measures to address the direct solar radiation since intense radiation can add unnecessary heat and glare (Ander, 2003).

2.2.4 Aperture size, shape, and window to wall ratio

The size of aperture has an obvious role to play in daylighting designs, but it is more complicated than just a simple understanding that larger window areas admit greater amounts of daylight than do smaller apertures. More glazing is not always necessary and more importantly not always better. The size of window impacts the potential for glare and Boubekri and Boyer (1992) in their research on daylighting in commercial buildings found that daylight glare reached its maximum when windows occupied one-half of the façade. Similarly, Ne'eman and Hopkinson (1970) surveyed 318 building occupants asking for their preferred window size using room models and found that windows occupying between 20-40% of the façade wall were most preferred, where rooms that had a .35 ratio satisfied 85% of the participants. Today's rule of thumb is a window to wall ratio of .30 (O'Connor *et al*., 1997), which nestles nicely within the recommended window area guidelines for ideal energy savings (Abdou, 1997).

Guidelines aside, it is equally important to remember the occupants for whom the building is intended. Aperture size should really be a reflection of the required illuminance level in the space (Baker & Steemers, 2002). To this end, the window to wall ratio is flexible depending on purpose and intention of the space and fortunately new glazing performance technologies (discussed later) mean that size need not be compromised for energy performance.

Preferred window size varies across different settings, though in general, larger windows are better than smaller windows and wider windows are better than taller ones (Galasiu & Veitch, 2006). Cuttle (1983) likewise concluded from her research that "the larger the windows are, the more desirable they are perceived to be." Perhaps this is because view plays a role again and should be considered in designing aperture size and shape. It has been found that occupants prefer a wider, more horizontal window when the view is closer (Ne'eman & Hopkinson, 1970). Horizontal window shape is best for views as vertical windows restrict skyline (Abdou, 1997). Furthermore, horizontal apertures are better than vertical to keep glare and contrast to a minimum. (O'Connor *et al*., 1997).

2.2.5 Orientation of windows

Arguably more important than the amount of glazing is how the glazing is distributed and where it is located. Indeed the orientation of windows impacts not only the potential amount of daylight, but also the design strategies necessary to optimize the available daylight. The following guidelines apply for northern hemisphere daylighting applications.

The fact is that windows on every orientation can offer useful daylight. However, it is important to recognize and understand that different orientations will benefit from different daylighting strategies (O'Connor *et al*., 1997). Windows facing north receive high quality consistent daylight with relatively minimal heat gains. In most circumstances shading is not even needed as the potential for glare and heat gain is very slight (Kwok & Grondzik, 2007). In support of this, a survey of 83 office workers by Osterhaus (2005) found that respondents with northern facing windows reported daylight glare less frequently than all other orientations. Windows that face south have access to very strong daylight, though it varies throughout the day. Therefore, southern facades are most often the best venue for exploiting daylight through larger apertures (Baker & Steemers, 2002). Horizontal shading is most effective on southern windowed façades where it can block all but the lower winter sun angles, when the sun is actually desired. However, the same horizontal shading proves ineffective on east or west elevations of buildings (Whole Building Design Guide, 2009). Here, shading is more difficult, while even more critical. East and west facing windows are subject to the lowest sun angles as the sun rises and sets and more notably windows to the west are large liabilities to a building's energy performance. Likewise, east and west facing windows bring the highest potential for glare (Kwok & Grondzik, 2007). When possible, it is suggested that unoccupied or non-air conditioned spaces be placed here (O'Connor *et al.*, 1997).

2.2.6 Glazing performance

While large amounts of glazing on a building once meant large amounts of heat transfer between indoor and outdoor environments, improvements in glazing technology today makes this assumption less true. A variety of coatings are now able to reduce the transfer of heat, obscure views for privacy, and most relevant here – reduce and/or diffuse the amount of light transferred thus clearly impacting daylighting design strategies. Visible transmittance (VT), which is a rating that reports the percentage of visible light striking the glazing that will pass through, is one glazing property that is important to pay attention to in daylighting designs.

A review of literature reveals that the preferred illuminance levels in offices with daylighting are incredibly variable from person to person and across tasks

(Galasiu and Veitch, 2006) and so it is impossible to point to one VT value for all settings. However though, while there is no single value for all applications of glazing (though there are formulas to use as guides) there are some rough recommendations. BetterBricks (2009) offers its own rule of thumb recognizing that a high visible transmission value can mean glare in the absence of shading or other glare reducing measures. For lower view windows without exterior shading a VT of lower than 0.40 will reduce glare while upper glazing windows a VT of greater than 0.50 is appropriate.

Recognizing that size of apertures has an obvious impact on the amount of admitted daylight, recommendations for VT values can be based on relative aperture size. O'Connor *et al.* (1997) put forward simple and relative guidelines of 0.70 for small windows, 0.50 for medium windows, and 0.30 for large windows. Along this vein, the discussion on appropriate aperture sizes becomes pertinent again in light of different glazing properties because the size of aperture alone does not determine illumination levels. The visible transmittance of the glass can reduce the "effective aperture" which is the product of the window to wall ratio and the visible transmittance of the glazing and so when sizing windows it is also important to account for the VT of the glazing. Ander (2003) states that when the effective aperture is around 0.18 daylighting saturation is achieved and so adding any more light will be counterproductive by increasing cooling loads more than reducing lighting loads.

New to the market are more dynamic coatings that can change with the exterior conditions. Photochromic, thermotropic, and electrochromic (switchable) windows are all different variations of new technologies used in "intelligent windows" (Inuoe, 2003). Each technology darkens or reduces the transparency of the glass when triggered by what is usually an environmental stimuli such as light, energy (temperature), or an electric current from a programmable source. As these technologies are still fairly new the final verdict is still out on their best applications and feasibility in all environments as well as the occupant responses to these automated controls (Inuoe, 2003).

2.2.7 Internal reflectance

Interior surfaces, characterized by their color and texture, also play a role in a daylighting strategy as they have the potential to further reflect and scatter the daylight. More important than that of any other interior surface in the daylighting strategy is the reflectance value for the ceiling (Ander, 2003). To ensure maximum reflectance off the ceiling it is best to keep the ceiling as light a color as possible, with a reflectance value over 80% (Whole Building Design Guide, 2009). Next in importance in the discussion on interior surface colors is the back wall followed by the side walls, which also should ideally be light colored. If dark finishes are desired in a space, they can be used on the floor where they are least impactful (Ander, 2003).

Surface textures are also important to consider when designing an interior daylit space as the texture is what decides the quality of light leaving the surface. Matte finishes will diffuse the reflected light, thus reducing glare, while smooth or glossy surfaces produce specular reflections, thus heightening the glare possibility (Kwok & Grondzik, 2007).

2.2.8 External shading strategies

External design features are one of the most effective strategies for stopping or limiting direct beam sunlight before it can reach the building. These shading strategies can either be fixed or mechanical/movable with the mechanical strategies reacting to the changing weather and sky conditions. Overhangs (or canopies) are a fixed shading method capable of blocking direct-beam radiation and are most appropriate above south facing windows. Additionally, depending on their positioning between two vertically-stacked windows (separate daylight and view windows), overhangs can also act as exterior light shelves catching and reflecting more light inside (Ander, 2003). Overhangs do not necessarily need to be solid or rectangular in construction, but can be punctuated as egg-crate baffles or more patterned or organic as many brise soleil designs are. There are differing aesthetic qualities for each type, but the obvious drawback for any type is its permanent placement and visibility on the façade, which any architect must reconcile with the overall building design (Phillips, 2004).

Horizontal louvers are simply mechanical versions of overhangs capable of being adjusted. They block direct-beam sunlight in summer time when the sun is high while still admitting sun at lower angles to enter in the cooler seasons. Vertical shading can come in the form of mechanical or fixed louvers, sometimes called fins. These shading devices are advantageous on east and west facades (Ander, 2003).

One, possibly less likely, shading solution comes in a more organic form. Plants and trees should also be considered as external obstructions to direct beam sunlight. In fact, plant shading can be more effective than any fixed shading strategy because plants, notably deciduous ones, are actually dynamic and while the autumn and spring equinoxes have identical sun positions, they do not have the same temperatures. Thus, when the warm September sun is out, the trees can provide shade, but when March approaches and the trees do not yet have their leaves the sun can be welcomed to help warm up the building (Kwok and Grondzik, 2007).

Finally, resting on the border, literally, between external and internal strategies exists the potential of using the building itself for shading. O'Connor *et al.* (1997) recommend taking a deep façade approach as a daylighting shading strategy because when a building has a deep façade the façade itself creates a buffer zone that can contain shading elements and other modifiers to filter glare and block sun.

2.2.9 Internal shading strategies

While any internal shading strategy is going to be less effective at minimizing heat gain than an external strategy (Phillips, 2004), interior strategies can still be very effective at eliminating excessive bright spots. There are a variety of internal shading controls, both manual and automatic, to choose from and there are advantages and disadvantages to each.

Venetian blinds allow for easy manual control by occupants, though for their optimal use they require frequent adjusting. In a study of six Maryland office buildings with approximately 700 venetian blinds it was found that occupants do not use these controls in any manner that relates to the sun position or daily or seasonal conditions. The study did find however that occupants in offices facing south had their blinds closed about 80% of the time, whereas occupants facing north only closed about 50% of the time (Rubin *et al*., 1978). Rea (1984) compared blind usage on different facades and in different weather conditions in a similarly conducted study in Canada and found that blind usage was the same (about 60% of blinds closed) on a clear day no matter the window orientation. The same was true on a cloudy day for all the orientations except for those facing east where only 40% of blinds were closed. Certainly, more spaces could benefit from natural light, even on an overcast day, but they miss out because blinds are not adjusted frequently enough. After a thorough review of previous research Galasiu and Veitch (2006) conclude that when manually operated shading devices are available, most often people will set them once and then rarely change them making them less than optimal for daylight shading.

Technology today has sought to address this with automated interior shadings. Lee *et al*. (1998) have found success in using automated venetian blinds linked to photosensors that not only meet occupant satisfaction levels, but also offer energy savings when connected to the electric system. Occupant behavior-based algorithms have been experimented with as a way of automating interior shades to optimize controls throughout the day (Inoue *et al*., 1988).

Draperies are another interior shading method that offer varying degrees of transparencies for a variety of light distributions. Furthermore, draperies/curtains offer the highest flexibility with their fabrics.

Roller shades are yet another method of internal shading that can be raised and lowered like blinds. However, unlike blinds they do not have slats capable of tilting to provide a view, but they can come in a variety of degrees of opaqueness. Therefore they are still a good candidate for reducing glare and direct-beam sunlight (Ander, 2003).

Overall, interior controls have the advantage over exterior controls of being able to be fully retracted when not needed, whereas exterior controls usually remain fixed and visible at all times. While another advantage of interior shading strategies may be the ability for occupants to adjust them to meet their comfort needs, this needs to be balanced with the energy performance of the room and daylighting intent which will be discussed in the next section.

2.2.10 Interface with electric lighting

A lighting system that relies solely on daylighting is incredibly rare if not altogether impossible in commercial buildings. Daylight almost always works in conjunction with an electric lighting system, which is necessary to supplement the lighting on days when the sky is overcast or after the sun sets in the late afternoon in the winter months. The interface between these two systems is a very important component to any daylighting approach.

Many commercial buildings today ignore the illuminance provided by daylight and attempt to increase energy performance only through occupancy sensors. More intelligent interfaces today allow for automated coordination with electric lighting using photosensors.

On/off photoelectric switching is a simple method where electric lights are switched off when a chosen daylight illuminance is reached in the room and then turned back on when illuminance falls below the set value. However, these systems can be very distracting if not programmed with a delay and are not the ideal method for energy savings (Baker & Steemers, 2002; Ander 2003). Another possibility to prevent distractions from on and off switching is to implement a scheduled switch off at a chosen time mid-day once the sun is presumed to be bright enough (Baker & Steemers, 2002). Otherwise, photoelectric switching may be best for bright perimeter zones where lights will be off most of the day anyways.

Stepped controls are a more sophisticated photoelectric interface that allow for intermediate levels of illuminance from electric lighting and provide a smoother and less perceptible transition between daylight and electric light by coordinating the use of multiple lamps. Additionally, rooms can be more comfortably lit with this method by allowing one ceiling lamp to always remain on to prevent the undesirable aesthetic of a dark ceiling (Ander, 2003).

Still more sophisticated than stepped controls are dimming interfaces between electric lights and daylight where there is continuous automatic adjusting of electric lighting levels based on real time daylight illuminance levels. Understandably, these systems provide the greatest potential for energy savings and also integrate well into existing energy management systems (Ander, 2003).

However, if a dimming system is desired appropriate lamps must be selected that are capable of such dimming.

With any lighting interface the occupant should be included in the equation. The general consensus today is that any automated lighting system must allow for occupant manual override or adjusting of the parameters if the occupants are to accept the systems (Lee *et al*., 1998; Galasiu & Veitch, 2006). However, the exact amount of control that should be given to occupants is still undergoing debate as it pertains to the consequences on energy efficiency (Lee *et al*., 1998). Additionally, experiments have been conducted linking too much lighting control in the workplace to a decrease in work performance as well as negative outcomes on occupant mood (Veitch, 2001). The interface with the occupant indeed needs to be simple and easy to use when provided (Galasiu & Veitch, 2006).

Providing supplementary task lighting to workstations and offices is an energy efficient complement to daylighting that does not require a complicated integration with daylighting or electric systems already in place. Task lighting, when appropriately located and maneuverable, can put control in the hands of the occupant when other controls are wrestled away from them.

3.1 Summary

In summary, while much is known today regarding best practices for daylighting, there is not and never will be a "one size fits all" strategy that will work for every single building. The exact opposite is true in fact as good daylighting should take a systems approach. Region, climate, building site and orientation, solar access, building purpose, and of course budget will all need to shape the design decisions. Each decision should be customized to the specific building while still reflecting current knowledge and standards and as much of the literature demonstrates, brand new research and technologies continue to make this a very exciting and dynamic design field in which to work. Daylighting, as the research shows, has a strong link with occupant well-being and therefore the time should be taken to discover and create the best strategy to ensure this well-being and the financial payback will follow. More than likely, the energy savings will pale in comparison to this.

My study will examine the daylighting strategy employed in a university campus laboratory building and aim to unfold the relationship between access to daylight and occupant comfort, satisfaction, and performance looking to discover the particular strategies that are most impactful. The literature suggests to me that I take a whole systems approach and also examine in an exploratory manner the daylighting controls used and also look at the most pertinent consequence of daylight: glare. After all, Bayer *et al*. (2006) in their committee interim report for the Massachusetts Technology Collaborative make a strong case for why the performance of any daylighting design cannot be studied in isolation citing the interplay of many components within the entire system. They conclude that all components must be looked at together including enclosure design, controls, space geometry, and finishes. My study will attempt to do this.

CHAPTER 3

METHODOLOGY

3.1 Research Design

In this explorative study I examined the actual daylighting design of a newly built university campus building and surveyed occupants for their perceptions of satisfaction, comfort, and perceived productivity while in the space. A daylighting design evaluation toolkit comprised of an occupant survey, illuminance meter, illuminance loggers, and glare-capturing camera and software was developed and used as a means of measuring the visual work environment's amount and distribution of light and its usefulness in laboratories and offices. These tools are described in further detail below.

The independent factors in this study were the measurements of lighting and daylighting conditions taken in the workspaces, including spot illuminance measurements on various worksurfaces and presence of glare (calculated through contrast ratios), as well as the researcher-observed daylighting design features such as type and shape of exterior shading, window size, and type of lighting controls, and finally the occupant distance to the facade. Floorplans, elevations and section drawings of the building were acquired to help code these features.

Occupant perceptions, were assessed through self-report surveys, which included questions regarding satisfaction with the visual environment, visual comfort and perceived productivity. Questions for the survey were compiled from two other surveys commonly used in post occupancy research on the built environment (Heerwagen & Zagreus, 2005; Abbaszadeh *et al*., 2006) – U.C. Berkeley's Center for the Built Environment IEQ Survey and the Center for Building Performance and Diagnostics Workplace User Satisfaction Survey developed at Carnegie Mellon University. Figures 3-1 through 3-3 show sample seven-point Likert scale questions used to assess satisfaction with the visual environment, visual comfort and also perceived performance. One question from the NIOSH job stress questionnaire was added as a control for negative affect, i.e. “How satisfied would you say you are with your job?” (four point scale). The complete survey can be found in Appendix A.

How satisfied are you with the following factors?

	Strongly disagree			Neutral			Strongly agree
Amount of daylight in this space	o	o	o	o	o	o	o
Distribution of light in this space	o	o	o	o	o	o	o

Figure 3-1. Sample questions for satisfaction

How satisfied are you with the following factors?

	Strongly disagree			Neutral			Strongly agree
Visual comfort of the electric lighting (e.g. glare, reflections, contrast)	o	o	o	o	o	o	o
Visual comfort of the daylighting (e.g. glare, reflections, contrast)	o	o	o	o	o	o	o

Figure 3-2. Sample questions for comfort

While working in THIS SPACE during an average week, I make FEWER technical errors than I did in my PREVIOUS WORKSPACE BEFORE moving.

Strongly disagree			Neutral			Strongly agree
o	o	o	o	o	o	o

Figure 3-3. Sample question for perceived performance

3.1.1 Measurement Toolkit

The measurement toolkit for this study was comprised of a Minolta T-10 illuminance meter, a Nikon Coolpix 8400 with a fish eye lens digital camera, and five light intensity loggers. A computer program called Photolux was used to assist in identifying the presence of glare from the photographs taken.

3.2 Apparatus/Setting

Weill Hall on Cornell University's campus in Ithaca, NY was chosen as the setting for this study. Cornell University is located in the Central New York Finger Lakes region where the local climate is typical of the northeast United States – cold winters and moderately hot and humid summers. The number of days of sunshine in Ithaca, NY is unavailable. However, hourly solar radiation data (using a solar pyranometer) collected from a meteorology center close to campus and affiliated with the Northeast Regional Climate Center shows that for the month of February between normal school hours of 8 and 5 the average hourly radiation is 17.48 langleys. The darkest day had an hourly average of 1.32 langleys while the brightest day had an hourly average of 32.03 langleys. The hourly average on the median day was 17.39 langleys.

Weill Hall (see Figure 3-4) was deemed a good setting for the study due to its LEED Gold rating, convenient location, ensured cooperation from staff, and the nature of the building being an academic laboratory building. University buildings are owned and operated for the long-term, making them good candidates for investment and further research and today we understand the large potential the physical environment has to support creative knowledge work. Furthermore, research regarding daylighting effects has not been extended to cover laboratory environments, which offer their own unique challenges due to a more technical nature of work.

Figure 3-4. Weill Hall from Northwest Angle

Weill Hall, recently completed in 2008, is home to several departments including Biomedical Engineering, Biological Statistics and Computational Biology, and the Joan and Sanford I. Weill Institute for Cell and Molecular Biology. The approximately 400 foot long building runs north to south with the great majority of the facades facing east or west. The building has four stories with the first floor set back roughly three feet below the others. Small scale vertical shading is a prominent feature used on the east and west facades. The east façade features fins more in the shape of triangular wedges as compared to the more rectangular fins on the west façade. Furthermore, horizontal shading is implemented on the first floor through the aforementioned three-foot setback. Figures 3-5, 3-6, and 3-7 show photos of the different shading strategies.

Inside Weill Hall, offices for the most part fall into one of three shapes and sizes: private rectangular office measuring 10’ by 18’, shared rectangular office measuring the same 10' by 18', or private "L" shaped office cut lengthwise into the footprint of 2 rectangular offices. All offices and labs have 12-foot high ceilings. Windows are large in all office types spanning the full façade wall beginning three feet off the floor and stretching to ceiling height. Furthermore, both private and shared offices on floors two, three, and four feature smaller box windows at floor level as well as longer horizontal windows above ceiling height. Refer to Figures 3-8 and 3-9 for an image of these windows. The windows in both the offices and labs have a visible transmittance of 0.7. The laboratories span long distances of the buildings and because the intention is to foster cross-group collaboration there are few dividers across the wide expanses. The large majority of the labs are on the east side of the building and again large windows flank the façade wall.

Offices have three hanging fluorescent tube light fixtures which all come on together with the control of a single light switch. On the second, third and fourth floors there is also another fluorescent light in the gap between the above-ceiling window and the dropped ceiling. This light is controlled by a second light switch. Fixed fluorescent underbin lights with diffusers are provided to occupants in the offices. Furthermore, offices, like the labs and rest of the interior spaces, have a high reflectance as all the interior walls are painted white. Figures 3-10 through 3-14 present images of the Weill Hall building.

Figure 3-5. Vertical shading strategy on west façade with rectangular fins

Figure 3-6. Vertical shading strategy on east façade with triangular fins

Figure 3-7. Building setback and horizontal shading on first floor

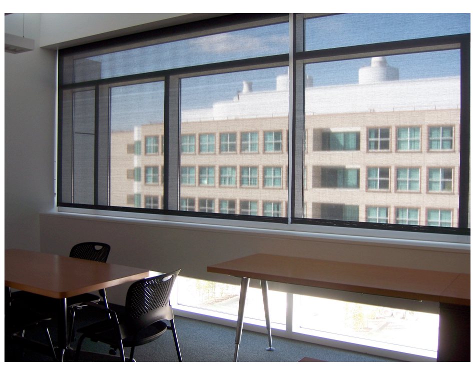

Figure 3-8. Floor height windows in offices

Figure 3-9. Above-ceiling height window

Figure 3-10. Laboratory spaces in Weill Hall

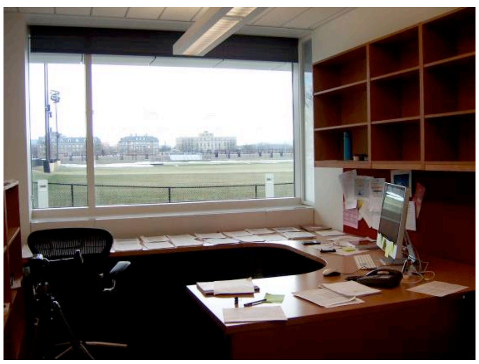

Figure 3-11. Private Rectangular Office

Figure 3-12. Shared Rectangular Office

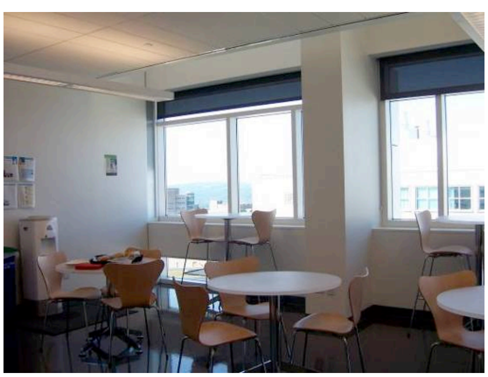

Figure 3-13. Departmental lounge

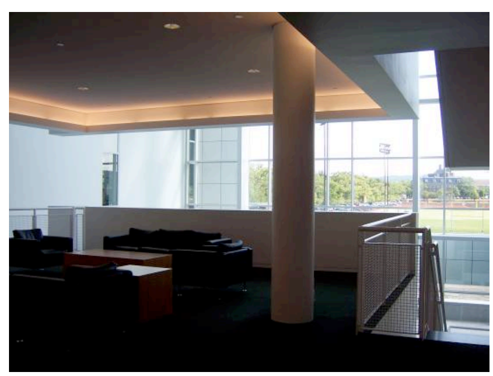

Figure 3-14. Lobby-atrium space on second floor

3.3 Participants

The participants were all occupants of the same campus building being studied. There were 75 participants comprised mainly of graduate students, post-docs, and faculty members. Administrative support staff, research staff, technicians, undergraduate students, and management personnel made up a small portion of participants. Figure 3-15 shows the breakdown of participants by position within the building. Due to small sample sizes in several of the positions, analyses could not be run on occupation/position. The average number of hours per week spent in the building by the participants was 44, with a high of 80, a low of 2, and a median of 45. Since the building was newly completed the longest anyone had occupied the space for at the time of research was 9 ½ months, with the average time being 5 ½ months. Less than ten percent of participants had occupied for fewer than four months. Figure 3-16 displays the frequencies for the different lengths of time since occupancy. The majority of participants were male, 57.3%, and the average age fell within the 21-30 year old bracket. Further, 78% of all participants fell within the larger 21-40 age bracket. Two participants were younger than 21 and five participants were older than 61. Figure 3-17 shows the age group breakdown of the participants.

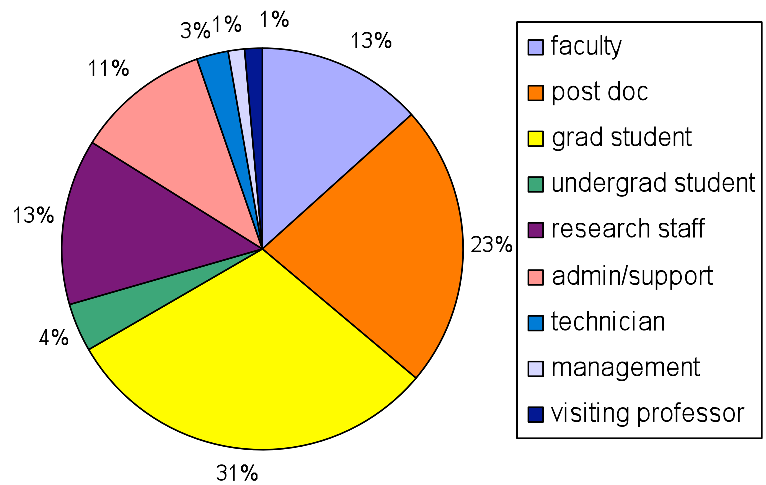

Figure 3-15: Breakdown of participants' positions within building

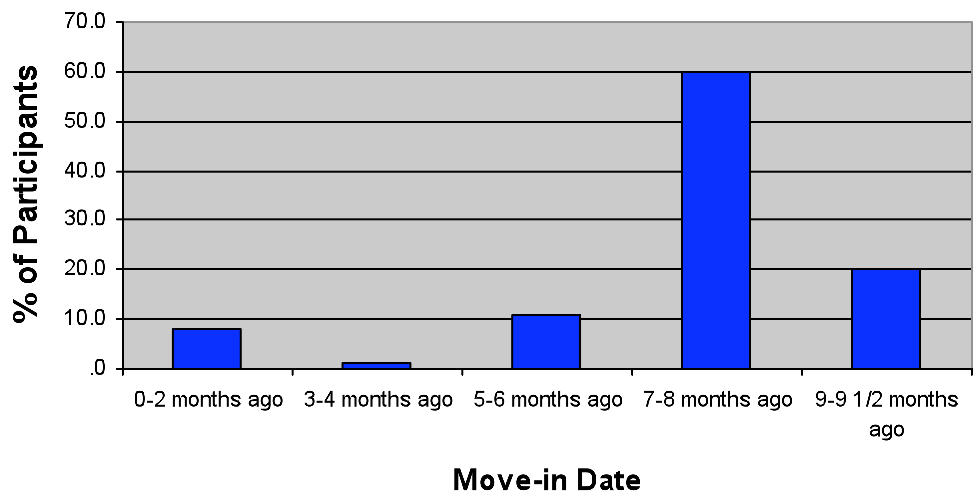

Figure 3-16: Length of Time since Occupancy

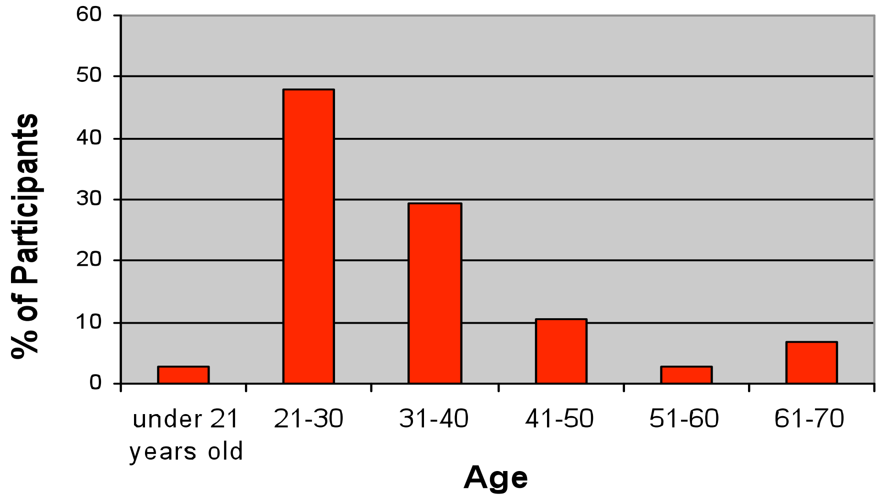

Figure 3-17. Participant Age Breakdown

The recruitment process began after receiving permission to study the building. With the cooperation of the facilities department, department chairs were contacted and asked to help spread word of the research study. On the days of surveying, occupants were approached in their workspace (lab, office, or cubicle) that they were currently working and asked to participate. About 1 in 9 declined to participate citing reasons including being too busy or needing to leave soon for a meeting or class. Written consent was obtained before the paper-based survey was administered or any lighting measurements were taken.

3.4 Procedure

Data collection spanned two consecutive weeks in mid-to-late-February 2009 with data collection occurring only on six of the days when the weather was deemed favorable enough. Favorable weather was defined as non-precipitating with the sky tending towards more sun than clouds. Weather was categorized as falling into one of three conditions: full sun, partly cloudy, and very cloudy, but still bright enough. Due to the sensitive nature of some of the research happening in the building I was only allowed into some labs on specific days and because of this a fourth weather condition was tolerated (slightly darker than very cloudy) on one of the six days of field study.

Solar data was collected approximately every two hours on days of surveying using the illuminance meter outside. These readings were used in conjunction with the solar radiation data available from the NRCC to create an understanding of the daylighting conditions on each day. These measures were then linked by time of day to occupant responses.

Two researchers at a time, always including myself and a research assistant, walked through the building looking for occupants in assigned workspaces, remaining in the east side of the building at times before noon, and on the west side of the building in the afternoon. Once a participant was identified and consent was obtained, a pre-survey checklist was administered by the one of the researchers. The purpose of the checklist was to record a description of the "As Is" lighting condition, specifically recording the number and location of artificial lights on, the current weather condition, and position of window shades, which was used to understand occupant use of available daylighting and control behavior. The complete checklist can be found in Appendix B. Next the occupant survey was given to the participant along with an oral clarification that the survey should be answered with respect to the space the occupant was currently in. Since many of the participants (57%) have both an office and a lab space, I needed to instruct the participant to focus only on the space I would be measuring to better establish the link between conditions and perceptions. However, as I was not granted permission to disturb some of the occupants in one department I opted to instead survey four occupants who I could approach in both their laboratory and their office setting.

While the participant was completing the survey, illuminance levels were measured at three points in the office – the computer monitor (omitted if no computer), keyboard (also omitted if not present), and primary work surface (as identified by the occupant). These three readings were repeated for four more lighting conditions for a total of five lighting scenarios: “As Is,” “ceiling lights off-shades fully open”, “ceiling lights on-shades fully open”, “ceiling lights on-shades half closed”, and “ceiling lights on-shades fully closed”. If the “As Is” condition to which I and my assistant came upon the occupant in was the same as any of the other four conditions, then that redundant condition was skipped. In this study the “As Is” condition was determined to hold special importance because it represented the lighting conditions that the occupant chose to work in at that time given the weather conditions of the day. To give strength to the use of spot illuminance measurements one question on the pre-survey checklist asked “are the lighting conditions in your space right now typical of how you have them at this time of day?” 96% of participants responded positively that the current conditions were typical.

Simultaneous to the illuminance spot measurements, photographs with the Nikon Coolpix 8400 were also taken. The camera was set up on a tripod (42 inches at desks and 48 ½ inches at lab benches) and positioned approximately two feet away from the computer monitor or bench to mimic the position the occupant assumes when at the computer or lab bench. Computer monitors were turned off as a measure of privacy. Photographs were taken for each of the first three lighting conditions (“As Is,” “ceiling lights off-shades open”, and “ceiling lights on-shades open”). Again, if the “As Is” condition happened to be ceiling lights off-shades open or ceiling lights on-shades open, then that repeated condition was skipped. The last two conditions were not photographed as the sole purpose of the camera was to capture glare which it was deemed would be reduced if not eliminated as the shades were lowered. For each lighting condition four photographs were taken, each with different camera settings:

- Aperture: 1/2, Speed 3.8
- Aperture: 1/15, Speed 3.8
- Aperture: 1/250, Speed 3.8
- Aperture: 1/1500, Speed 7.7

These four photos were uploaded to Photolux which created a composite image used to identify the brightness contrast ratio. The average lux values for both the immediate visual field (computer monitor screen in offices and an approximately similarly-sized area on the lab bench in labs) and the entire background (everything outside the monitor) were calculated and used to determine a contrast ratio. Occupants with ratios greater than 1:10 were considered to have glare present. This method of looking at the brightness contrast ratio allows for the identification of both direct glare and veiling reflections. If veiling reflections on the computer monitors were present in the photo, the percentage of the screen with reflections was recorded.

Approximately one week after the field study component was completed, light intensity loggers were placed in five vacant work spaces in the building – two laboratories and three offices. These loggers were then re-positioned every two days for a total of three positions in six days at varying distances to the window. These loggers recorded in footcandles and this data was used to help understand the daylight distribution in the different workspaces. Figures 3-18 and 3-19 exhibit the different placements of the loggers in both a laboratory and an office respectively.

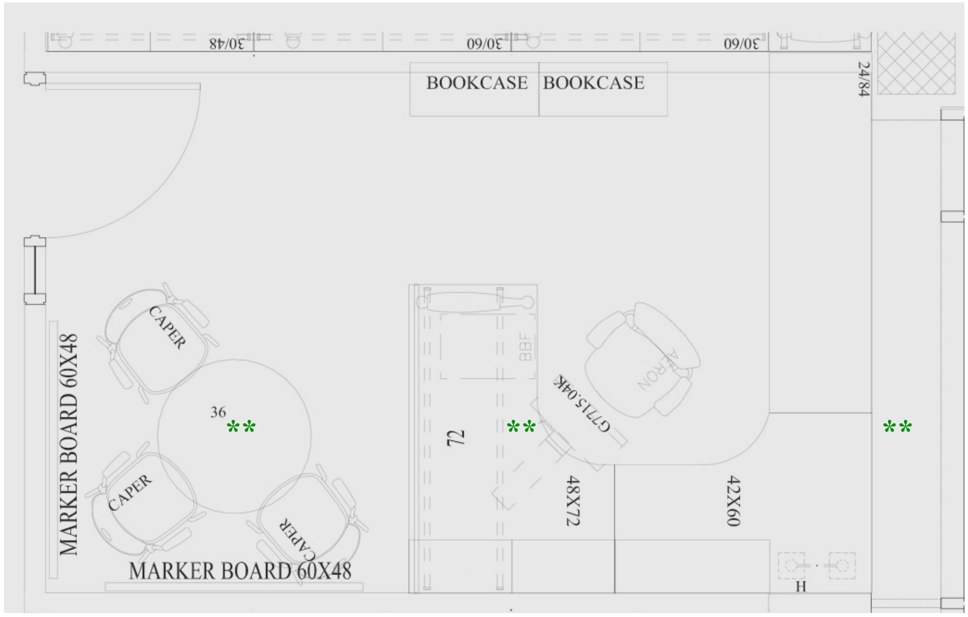

Figure 3-18. Diagram of logger placement in an office (marks the placements recorded for 48 hours)**

Figure 3-19. Diagram of logger placement in a laboratory (marks the placements recorded for 48 hours)**

CHAPTER 4

RESULTS

This study aimed to (1) discern if access to daylight affected occupant comfort, satisfaction, and perceived performance and (2) to discover what characteristics of daylighting design are associated with occupant comfort, satisfaction and perceived performance. These two questions guided the data analysis and provided a base from which to pursue greater exploration.

4.1 Descriptive Statistics

The software program SPSS was used to analyze the data. The first step was to understand participant satisfaction with the visual environment. The means for all the attributes rated for satisfaction were calculated. Refer to Table 4-1 for a summary and Figure 4-1 for a comparison of means. Figure 4-2 displays a distribution of the satisfaction ratings. Seven out of the 75 occupants surveyed were in offices without windows. Though making for a relatively small sample size, later tests were run between these two groups – windowed and windowless. Pre-occupancy “window conditions” were assessed on the survey and 9 participants reported not having a window in their previous workspace as compared to the 7 participants currently without a window in Weill Hall.

Table 4-1. Means, Standard Deviations, & Ranges for Satisfaction with Attributes of Visual Environment

Satisfaction with	Mean	Standard Deviation	Min	Max
Amount of Light	6.07	1.369	1	7
Distribution of Light	5.93	1.308	1	7
Amount of Daylight	5.87	1.781	1	7
Distribution of Daylight	5.37	1.814	1	7
Visual comfort of electric lighting	5.45	1.605	1	7
Visual comfort of daylighting	5.00	1.808	1	7
Amount of control over electric lighting	5.43	1.561	1	7
Amount of control over daylighting	5.47	1.565	1	7
Amount of light for paper-based tasks	5.57	1.570	1	7
Amount of light for computer work	5.52	1.545	1	7
Quality of lighting in general	5.88	1.365	1	7

Value	Label
1	Very dissatisfied
4	Neutral
7	Very satisfied

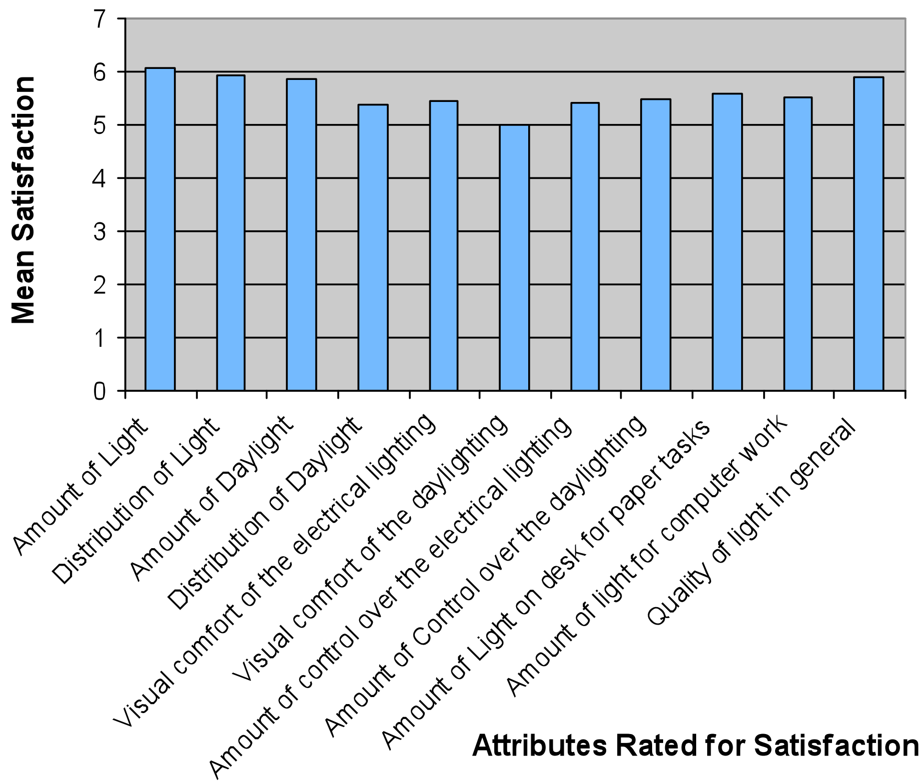

Figure 4-1. Comparison of Means for Attributes of Visual Environment

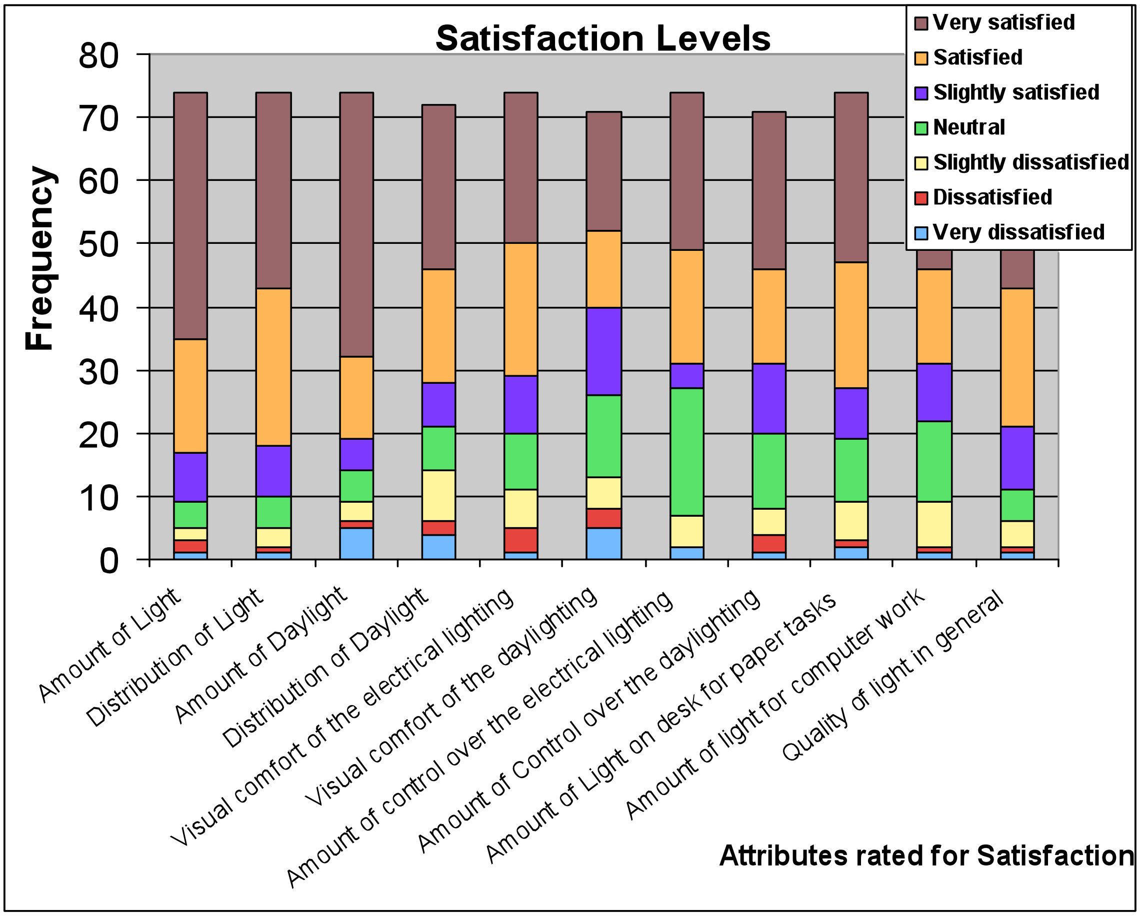

Figure 4-2. Distribution of satisfaction levels for attributes of visual environment

Table 4-2 displays the means for additional outcome variables. On average, all Weill Hall occupants rated satisfaction with the visual environment a 5.53 on a 7-point scale. Furthermore, it was found that occupants felt that the daylighting in their workspace offered support, rather than interference, to their work, rating it a 5.54 on a 7-point scale. However, it can not be said with as much confidence that access to daylight is related to better performance or productivity as occupants averaged only a 4.29 rating on the same 7-point scale, demonstrating only a slightly greater than neutral rating.

Table 4-2. Descriptives for Additional Outcome Variables

Outcome Variable	Mean	Standard Deviation	Min	Max
Satisfaction with Visual Environment	5.53	1.473	1	7
Visual Environment supports work	5.75	1.357	2	7
Daylighting supports work	5.54	1.529	1	7
Fewer errors made at work as compared to previous workspace	4.29	.941	1	7

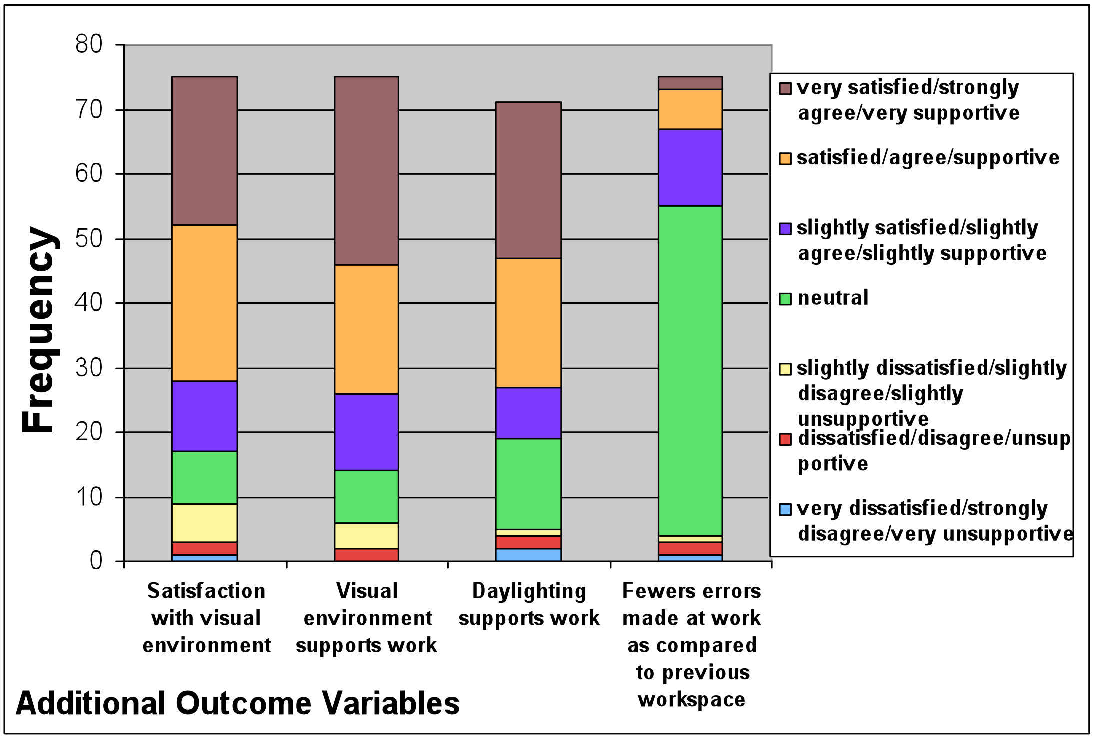

Figure 4-3. Distribution of additional outcome variables of the visual environment

4.2 Factor Analysis

Factor analysis was conducted to identify factors that might statistically explain the variation or covariation among the 11 items/attributes. Two factors were identified using the principal components analysis with a direct oblimin rotation due to likely correlations among the items. The first factor (Eigenvalue of 6.916) explains

62.87% of the variance and the second factor identified (Eigenvalue 1.348) explains another 12.26% of the variance for a combined total of 75.13% of the variance among the items explained. Table 4-3 shows the factor loading of the 11 items/attributes and quite visibly seven items predominantly load onto Factor 1 while the other four predominantly load onto Factor 2. Upon examination of the factor loadings it became apparent what the two underlying factors of satisfaction might be. Items that ask explicitly about "daylight" or "daylighting" load onto Factor 2 whereas items that do not reference daylight, but instead refer to electric lights or lighting in general cluster onto Factor 1.

Table 4-3. Factor Loadings for Items/Attributes Rated for Satisfaction with a Direct Oblimin Rotation

	Component/Factor	
	1	2
Amount of Light for computer work	**.921**	-.081
Amount of control over electric lighting	**.892**	-.138
Amount of light for paper-based tasks	**.873**	-.004
Amount of light	**.852**	.081
Quality of lighting in general	**.838**	.161
Distribution of light	**.625**	.357
Visual comfort of electric lighting	**.571**	.324
Distribution of daylight	-.028	**.936**
Visual comfort of daylight	-.079	**.917**
Amount of control over daylighting	.073	**.799**
Amount of daylight	.180	**.675**

To check if the newly clustered items were measuring the same factors, Cronbach Alphas for both clusters were calculated. As Table 4-4 shows the measures of internal reliability were fairly high.

Table 4-4. Cronbach Alpha values for Factor 1- General Lighting Quality and Factor 2- Daylighting Quality

	Cronbach Alpha
Factor 1- General Lighting Quality	0.94
Factor 2- Daylighting Quality	0.88

4.3 Correlations

Table 4-5 shows a correlation matrix, used to better visualize the relationships among the items. The significant correlations ($p < 0.05$) above 0.6 are highlighted in yellow. This correlation matrix supports the findings from the factor analysis (with only two exceptions) that items having to do with daylighting correlate with each more so than with items having to do with electric lighting or lighting in general.

Table 4-5. Correlation Matrix Between Attributes of Visual Environment Rated for Satisfaction

		Amount of Light	Distribution of Light	Amount of Daylight	Distribution of Daylight	Visual Comfort of Electric Lighting	Visual comfort of daylighting	Amount of Control over electric lighting	Amount of control over daylighting	Amount of Light for Paper-based tasks	Amount of light for computer work	Quality of lighting in general
Amount of Light	Pearson Correlation											
	Sig. (2-tailed)											
Distribution of Light	Pearson Correlation	.802**										
	Sig. (2-tailed)	.000										
Amount of Daylight	Pearson Correlation	.636**	.588**									
	Sig. (2-tailed)	.000	.000									
Distribution of Daylight	Pearson Correlation	.502**	.574**	.728**								
	Sig. (2-tailed)	.000	.000	.000								
Visual Comfort of Electric Lighting	Pearson Correlation	.700**	.665**	.631**	.573**							
	Sig. (2-tailed)	.000	.000	.000	.000							
Visual comfort of daylighting	Pearson Correlation	.359**	.575**	.570**	.709**	.494**						
	Sig. (2-tailed)	.002	.000	.000	.000	.000						
Amount of Control over electric	Pearson Correlation	.676**	.490**	.405**	.370**	.682**	.354**					
	Sig. (2-tailed)	.000	.000	.000	.001	.000	.002					
Amount of control over daylighting	Pearson Correlation	.499**	.543**	.482**	.761**	.492**	.712**	.431**				
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000	.000				
Amount of Light for Paper-based	Pearson Correlation	.724**	.749**	.458**	.400**	.550**	.432**	.632**	.494**			
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000	.000	.000			
Amount of light for computer work	Pearson Correlation	.692**	.692**	.409**	.363**	.574**	.416**	.708**	.496**	.783**		
	Sig. (2-tailed)	.000	.000	.000	.002	.000	.000	.000	.000	.000		
Quality of lighting in general	Pearson Correlation	.865**	.820**	.588**	.577**	.697**	.523**	.715**	.590**	.789**	.799**	
	Sig. (2-	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	

**correlation is significant at the 0.01 level (2-tailed)

With this recognition and confirmation of two new factors (hereafter called Factor 1- General Lighting Quality and Factor 2- Daylighting Quality) tests were run using these factors in addition to the initial eleven items. Correlation analysis was conducted with these new factors and another set of outcome variables to further understand occupant levels of satisfaction with the visual environment and their perceptions of performance. Refer to Table 4-6 for the correlation matrix. Significant correlations ($p < 0.05$) are highlighted in yellow and it can be seen that both Factor 1- General Lighting Quality and Factor 2- Daylighting Quality significantly correlate with perceptions of how the visual environment supports work. However, the survey's primary measure of performance, regarding amount of errors made, was not found to significantly correlate with Factor 1- General Lighting Quality or Factor 2- Daylighting Quality, though it did have a significant but low correlation of .266 with overall satisfaction with visual environment.

Table 4-6. Correlation Matrix between Factor 1 + Factor 2 and occupant satisfaction and perceptions of performance

		Satisfaction with visual environment	Visual environment supports work	Daylight supports work	Fewer Errors made at work as compared to previous workspace	Factor 1 (REGR)- General Lighting Quality	Factor 2 (REGR)- Daylighting Quality
Satisfaction with visual environment	Pearson Correlation						
	Sig. (2-tailed)						
Visual environment supports work	Pearson Correlation	.623**					
	Sig. (2-tailed)	.000					
Daylight supports work	Pearson Correlation	.471**	.596**				
	Sig. (2-tailed)	.000	.000				
Fewer Errors made at work as compared to previous workspace	Pearson Correlation	.266*	.207	.017			
	Sig. (2-tailed)	.021	.075	.887			
Factor 1 (REGR)- General Lighting Quality	Pearson Correlation	.648**	.381**	.202	.069		
	Sig. (2-tailed)	.000	.001	.093	.567		
Factor 2 (REGR)- Daylighting Quality	Pearson Correlation	.662**	.387**	.599**	.000	.578**	
	Sig. (2-tailed)	.000	.001	.000	.999	.000	

**correlation significant at the 0.01 level
*correlation significant at the 0.05 level

4.4 Design Characteristics

As it was noted earlier, there were 7 occupants surveyed, who either worked in an interior windowless office or in a cubicle in a bullpen style space, that did not have direct access to daylight through a window as all the other participants did. These seven individuals made it possible to examine the impact of windows by running a between groups test using a univariate general linear model, which also allowed for controlling of job satisfaction, a measure used to represent negative affect. It was found with a significance level of .065 after controlling for job satisfaction that occupants in windowed workspaces (n=68) rated satisfaction with their visual environment a 5.66 while the windowless occupants (n=7) rated it only a 4.29. Figure 4-4 shows boxplots of the satisfaction levels. Additionally, at a significance level of .082, occupants in windowed spaces had an average Factor 2 score, again which was generated through factor analysis representing daylighting relevant attributes of the visual environment, of 0.057 while those without windows had -0.949 score.

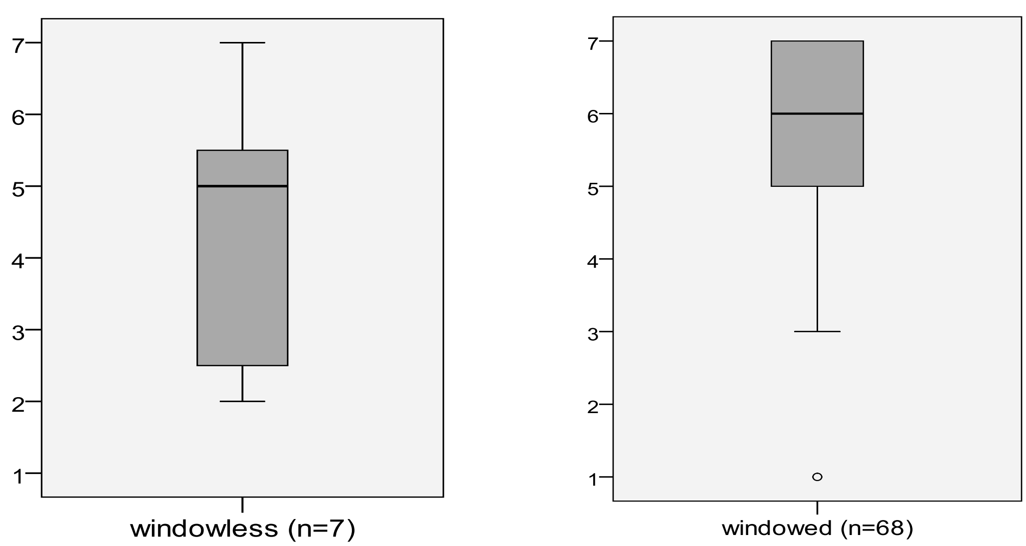

Figure 4-4. Satisfaction with Visual Environment for Workspaces with and without Windows

To answer my second research question – *what characteristics of daylighting design are associated with occupant comfort, satisfaction and perceived performance?* – I used a univariate general linear model in order to also be able to control for job satisfaction. Many of the design characteristics (both facade design and whole building design) in Weill Hall had only two conditions, but one variable – 'desk position with relation to window' – had three conditions. The characteristics I conducted statistical tests on included horizontal shading (present/absent), vertical shading (present/absent), shape of vertical shading (rectangular/triangular), orientation of window (east/west), desk position with relation to window (interior/perimeter/core), and lastly, workspace (lab or office).

Of these design characteristics, horizontal shading was found to have the most significant relation to occupant comfort, satisfaction and perceived performance. Table 4-7 shows means and corresponding significance levels of satisfaction levels for key attributes found to have significant levels of variance among the occupants explained by the presence of horizontal shading. Refer to Figures 4-5 through 4-8 for boxplots of these findings. Table 4-8 and Figures 4-9 and 4-10 report the significant findings for the additional outcome variables tested against the presence of horizontal shading (n=29).

Table 4-7. Significant ($p < 0.10$) Findings on Horizontal Shading

	Significance		Means
Satisfaction with visual comfort of daylighting	0.050	Present	**5.62**
		Absent	4.69
Satisfaction with amount of control over daylight	0.073	Present	**5.97**
		Absent	5.31
Satisfaction with amount of light for computer work	0.079	Present	**5.90**
		Absent	5.21
Satisfaction with distribution of daylight	0.098	Present	**6.00**
		Absent	5.26
Factor 2 (Daylighting Quality)	0.072	Present	**0.328**
		Absent	-0.150

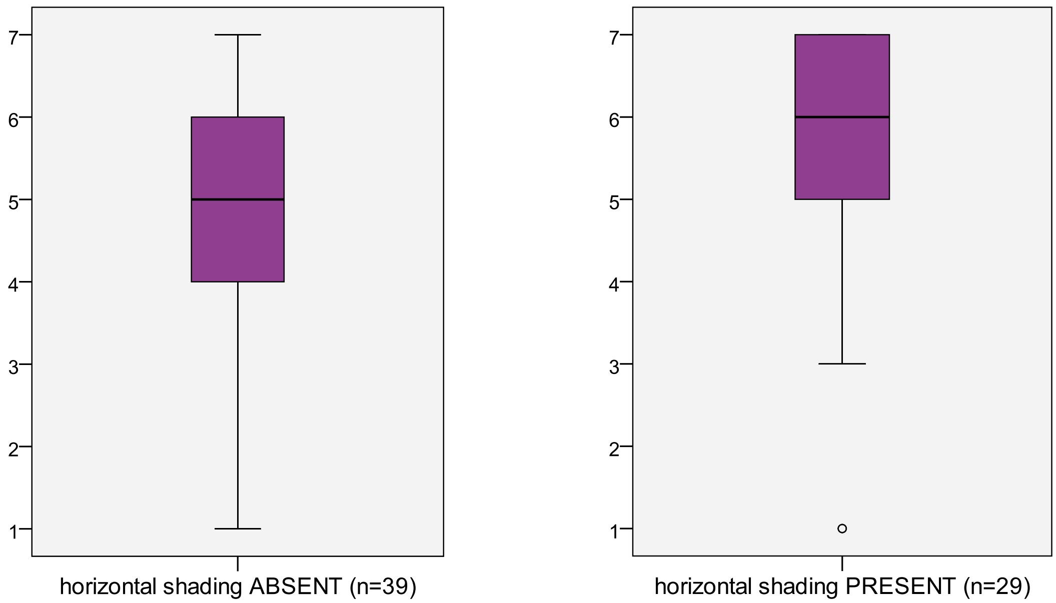

Figure 4-5. Satisfaction with Visual Comfort of Daylighting for Horizontal Shading

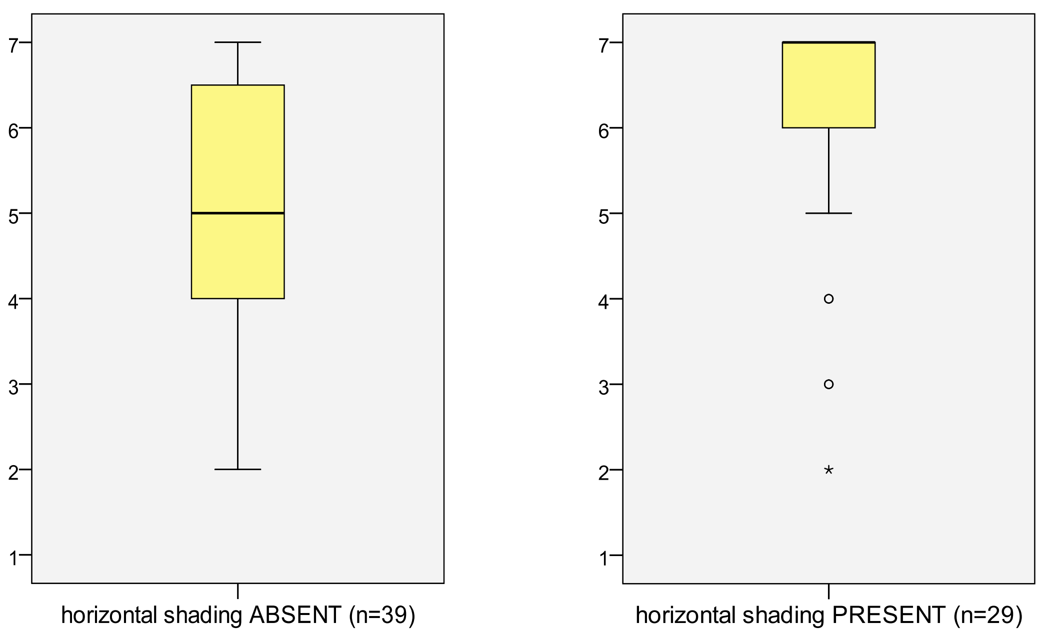

Figure 4-6. Satisfaction with Amount of Control over Daylighting for Horizontal Shading

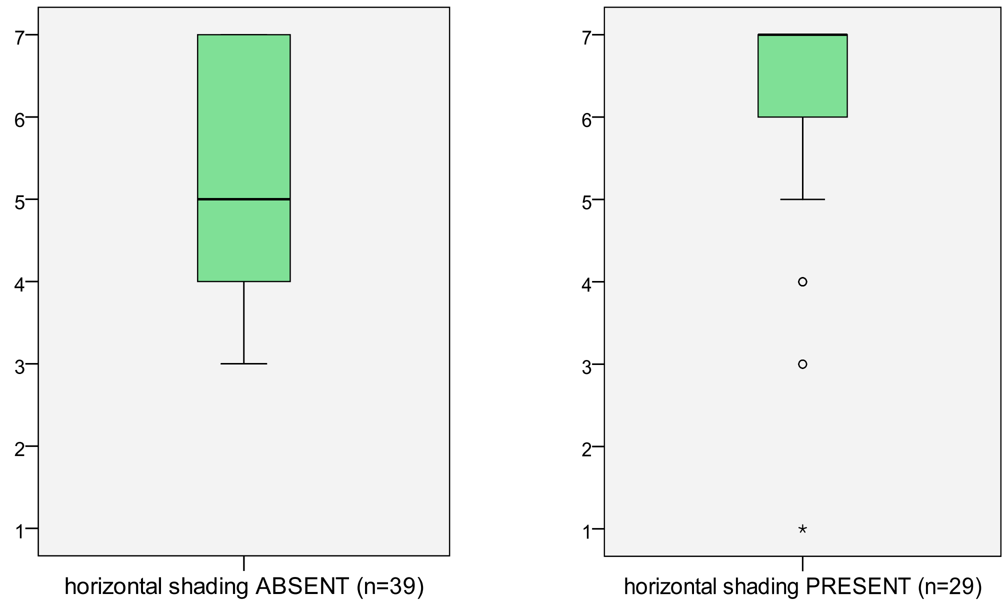

Figure 4-7. Satisfaction with Amount of Light for Computer Work for Horizontal Shading

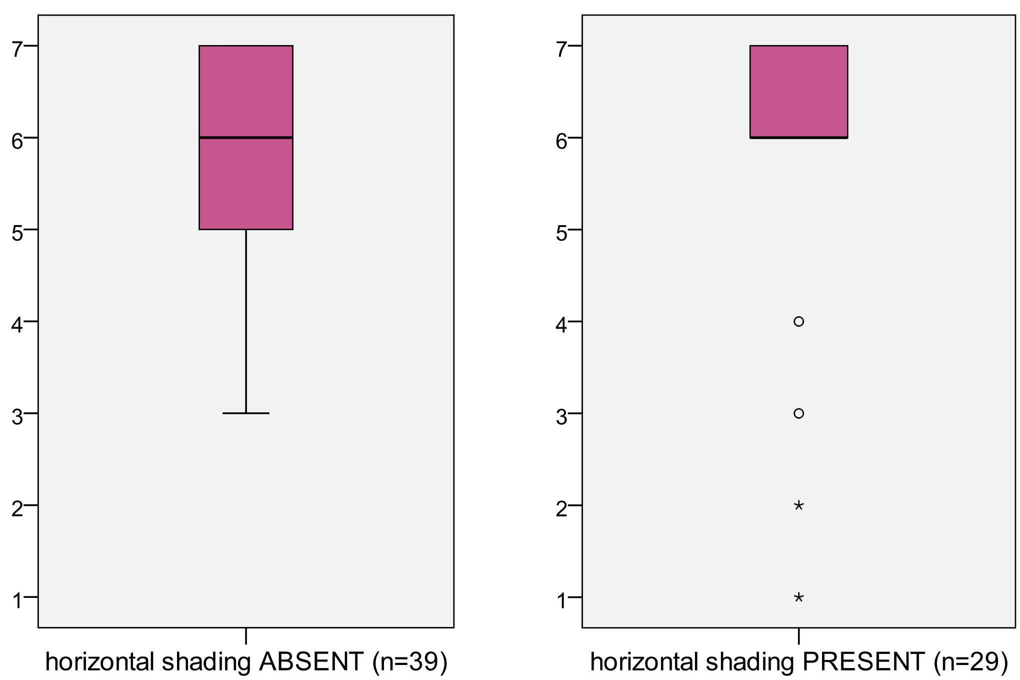

Figure 4-8. Satisfaction with the Distribution of Daylight for Horizontal Shading

Table 4-8. More Significant (p < 0.05) Findings on Horizontal Shading

	Significance		Means
Daylighting supports work	0.009	Present	**6.14**
		Absent	5.15
Visual environment supports work	0.015	Present	**6.28**
		Absent	5.46

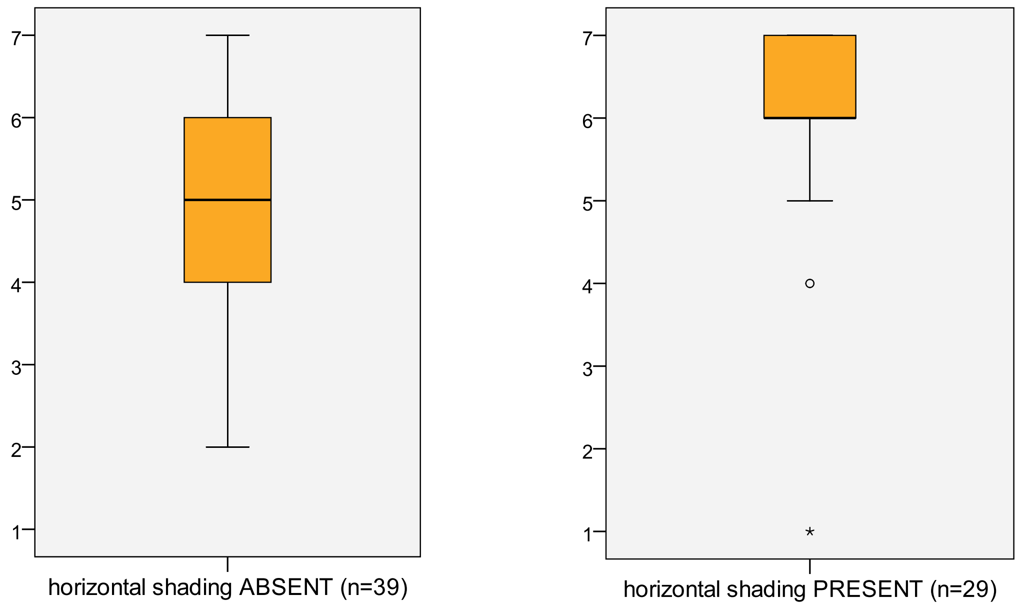

Figure 4-9. Support for Work from Daylighting for Horizontal Shading

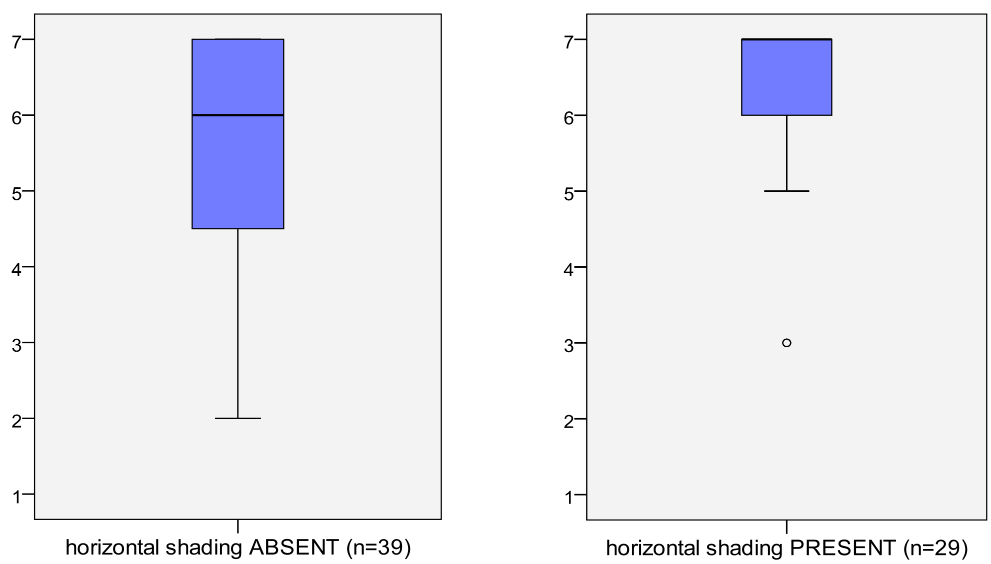

Figure 4-10. Support for Work from Visual Environment for Horizontal Shading

Statistical tests, still controlling for job satisfaction, performed on vertical shading showed that occupants whose workspaces had vertical shading (n=36) actually reported lower levels of satisfaction on several attributes. No findings were significant which showed the presence of vertical shading to relate to a higher satisfaction level. Table 4-9 reports these counter-intuitive means.

Table 4-9. Significant ($p < 0.10$) Findings on Vertical Shading

	Significance		Means
Satisfaction with distribution of daylight	0.087	Present	5.28
		Absent	**5.94**
Visual environment supports work	0.092	Present	5.56
		Absent	**6.09**
Daylighting supports work	0.019	Present	5.19
		Absent	**6.00**

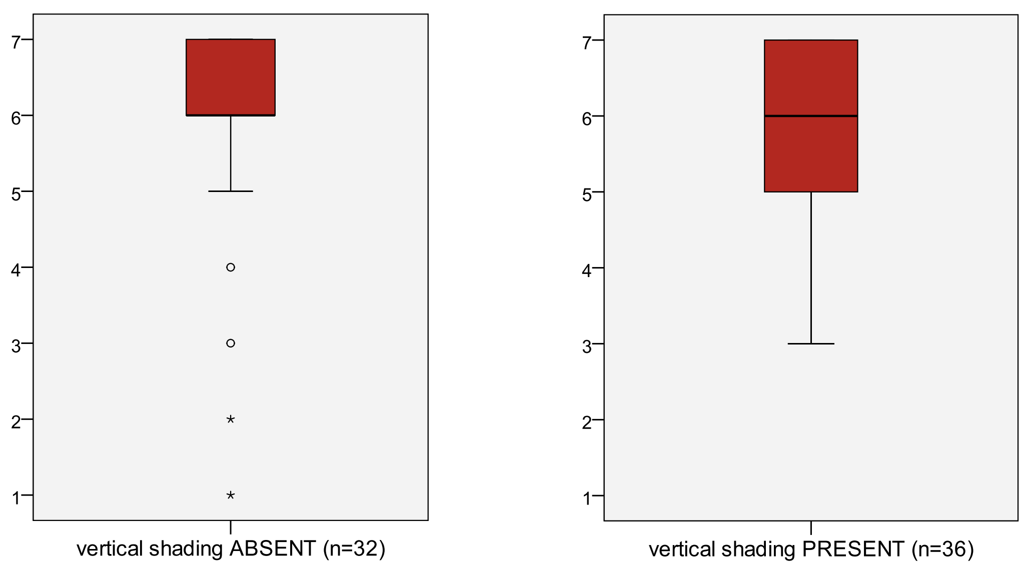

Figure 4-11. Satisfaction with Distribution of Daylight Visual Environment for Vertical Shading

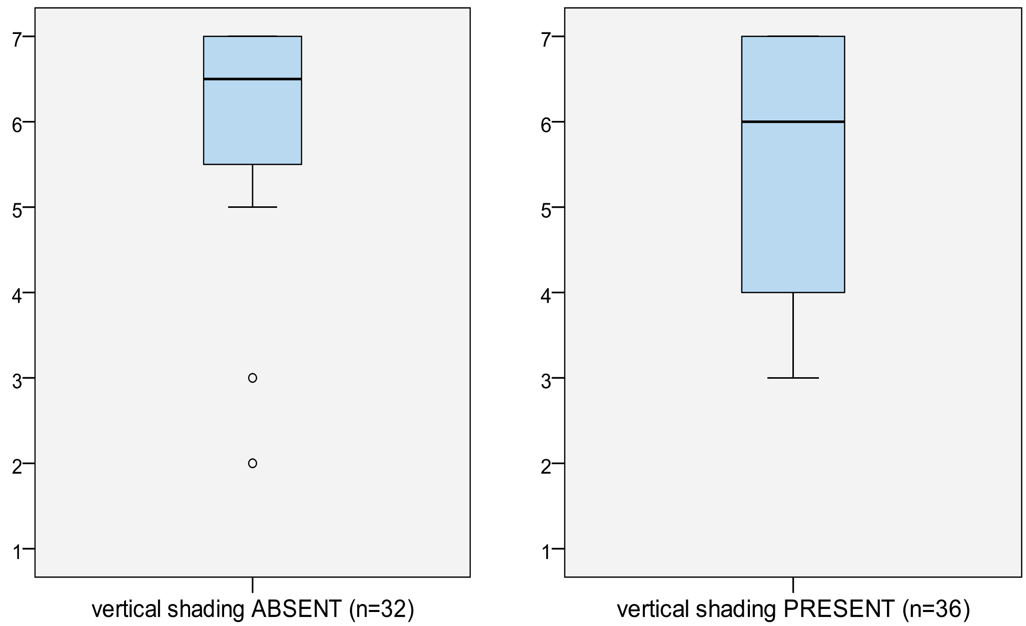

Figure 4-12. Support for Work from Visual Environment for Vertical Shading

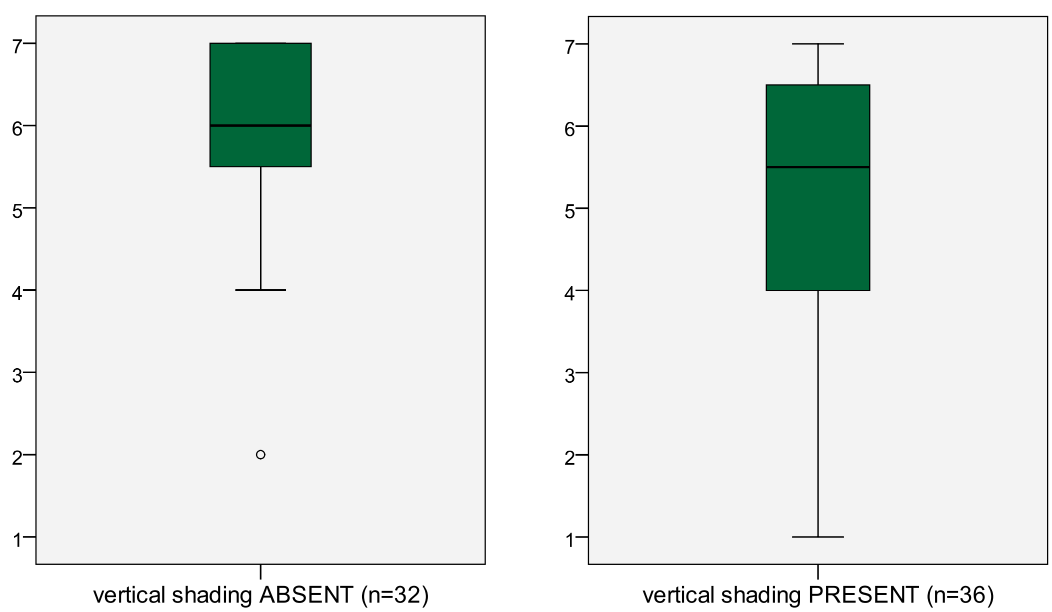

Figure 4-13. Support for Work from Daylighting for Vertical Shading

Tests run on the shape of vertical shading (n=18 for both shapes) only found one attribute of the visual environment that had a significant relation ($p < 0.10$) to satisfaction levels reported. Table 4-10 and Figure 4-14 shows the findings with regard to the attribute amount of daylight.

Table 4-10. Significant ($p < 0.10$) Findings on Shape of Vertical Shading

	Significance		Means
Satisfaction with amount of daylight	0.060	Rectangular	5.50
		Triangular	**6.33**

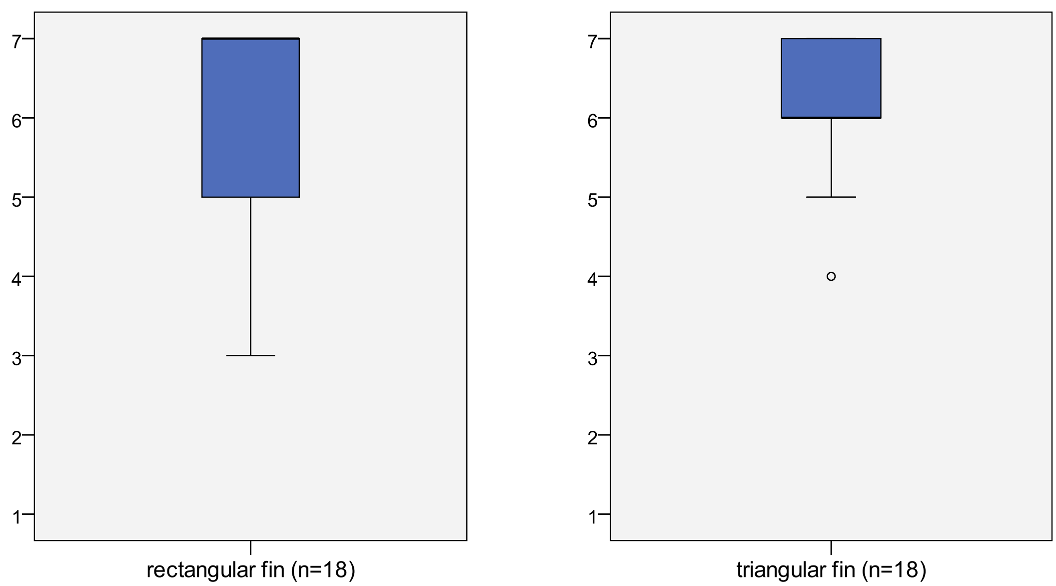

Figure 4-14. Satisfaction with Amount of Daylight for Shape of Vertical Shading

The orientation of windows was found to have only one significant relation to the outcome variables. Occupants with east facing windows (n=44) reported to a greater degree that the daylighting in their workspace supported their work than those with west facing windows (n=31) on average (5.80 to 5.19; p = 0.058). Small sample sizes prevented statistical tests from being run on desk positions with relation to windows. And lastly, tests run on workspace type, lab (n=25) or office (n=48) (cubicles were ignored as only two were surveyed), reveal a few significant findings reported in Table 4-11 and displayed in Figures 4-15 and 4-16.

Table 4-11. Significant (p < 0.10) Findings on Type of Workspace

	Significance		Means
Satisfaction with the amount of light for computer work	0.025	Office	**5.85**
		Lab	5.00
Satisfaction with the amount of light for paper-based tasks	0.070	Office	**5.81**
		Lab	5.28

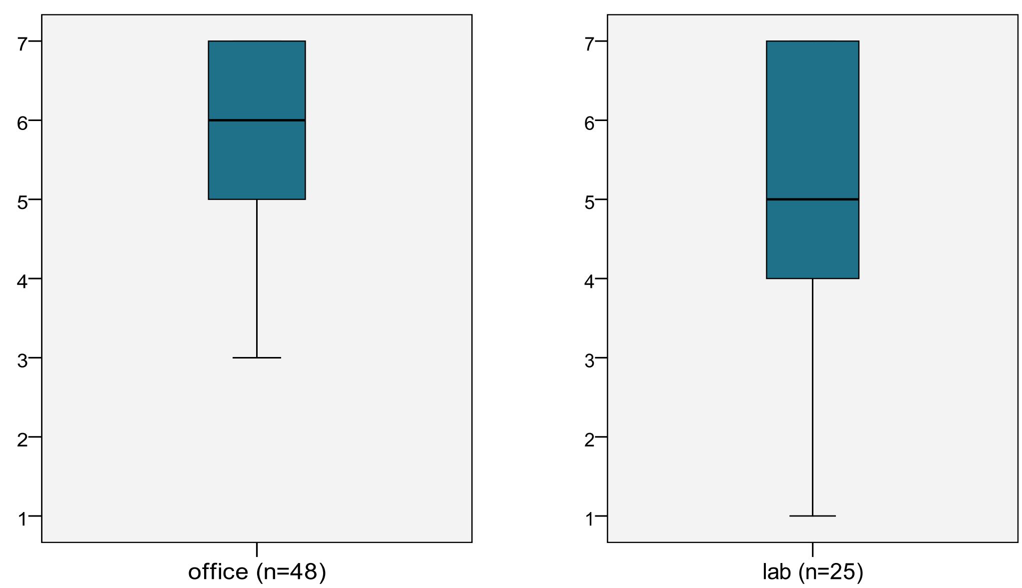

Figure 4-15. Satisfaction with the amount of light for computer work between offices and labs

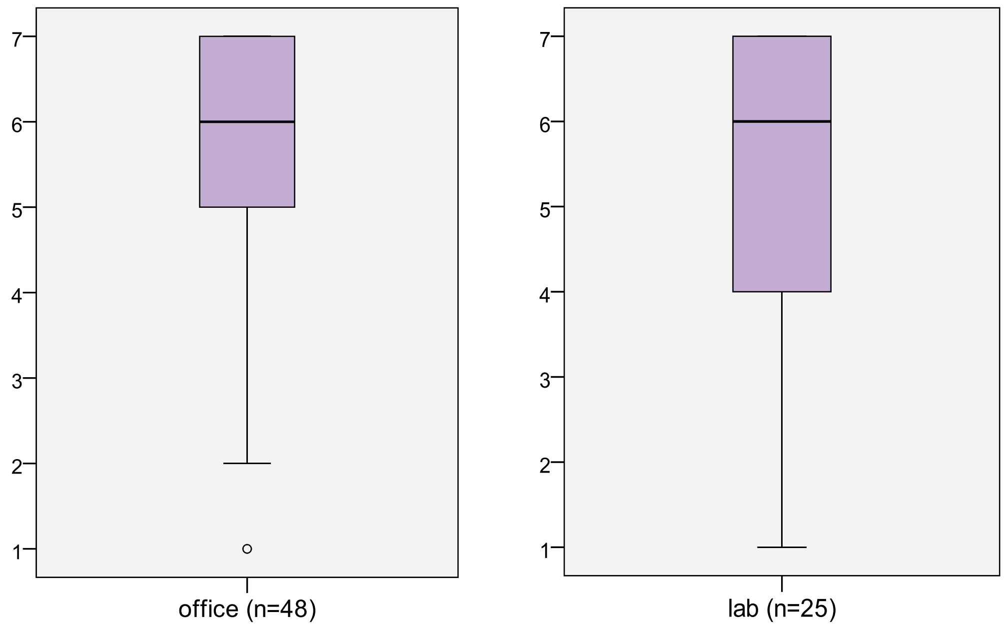

Figure 4-16. Satisfaction with the amount of light for paper-based tasks between offices and labs

4.5 Problems/Sources of Dissatisfaction

As the results show, simple access to daylighting alone does not unanimously lead to greater comfort, satisfaction, and perceived performance. The opportunity was there in the data to better understand what the sources and causes of dissatisfaction might be which were hindering occupant satisfaction. Previous literature suggested several features to probe and my survey allowed me to investigate two such features: glare and lighting controls.

Not all participants expressed dissatisfaction with at least one aspect of the visual environment (45 did not), but the 30 who did allowed me to probe deeper into the sources of dissatisfaction. Figure 4-17 presents the frequency of occupants expressing dissatisfaction with individual problems. As demonstrated in the graph, the most commonly reported source of dissatisfaction was reflections from daylight on computer screens and very likely, this type of complaint would be even more common in the warmer months when the sun angle is higher.

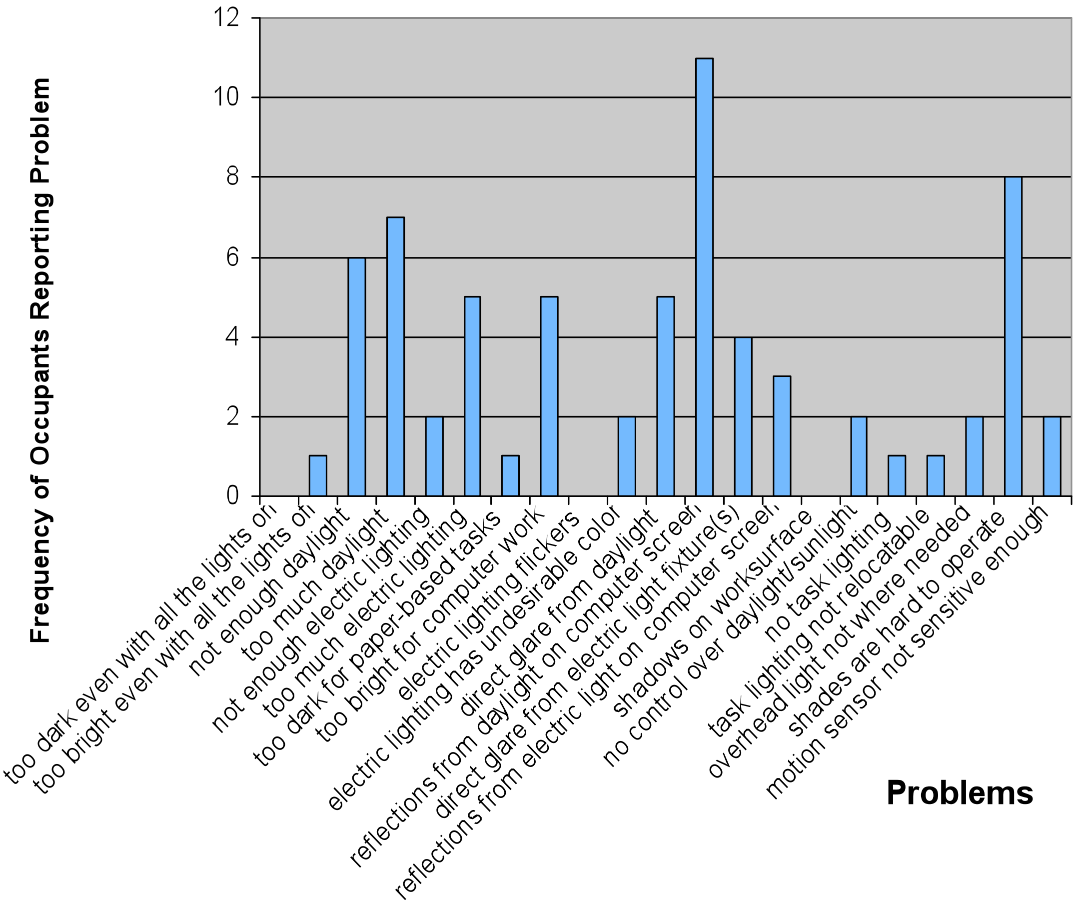

Figure 4-17. Frequency of Occupants Reporting Problems (N=30)

The first step was to confirm the likely (and possibly obvious) suspicion that lack of satisfaction with the visual environment arises from various problems. I did this by separating the occupants into two groups – those who continued on with the second half of the survey as instructed to if they rated answers worse than neutral and those who did not continue on with the “problems” section of the survey. Next, an independent sample t test was conducted to evaluate the hypothesis that participants who reported problems were more dissatisfied with their visual environment. For nearly all of the attributes rated for satisfaction, occupants who reported sources of dissatisfaction averaged significantly lower satisfaction ratings as compared to occupants who did not report dissatisfaction. Table 4-12 demonstrates these findings reporting means and significance levels with significant differences highlighted in yellow.

Table 4-12. Independent Sample t tests for average satisfaction ratings

	Sig 2 Tailed	Listed Any Problems	Mean
Amount of Light	0.056	no	6.33
		yes	5.67
Distribution of Light	0.029	no	**6.22**
		yes	5.50
Amount of Daylight	0.001	no	**6.49**
		yes	4.93
Distribution of Daylight	0.000	no	**6.07**
		yes	4.31
Visual Comfort of Electric Lighting	0.003	no	**5.93**
		yes	4.73
Visual comfort of daylighting	0.004	no	**5.53**
		yes	4.11
Amount of Control over electric lighting	0.052	no	**5.73**
		yes	4.97
Amount of control over daylighting	0.004	no	**5.93**
		yes	4.70
Amount of Light for Paper-based tasks	0.021	no	**5.91**
		yes	5.07
Amount of light for computer work	0.036	no	**5.84**
		yes	5.03
Quality of lighting in general	0.013	no	**6.22**
		yes	5.37
Satisfaction with visual environment	0.003	no	**5.98**
		yes	4.87
Visual environment supports work	0.002	no	**6.18**
		yes	5.10
Daylighting supports works	0.103	no	5.80
		yes	5.08
Fewer errors made at work as compared to previous workspace	0.843	no	4.31
		yes	4.27
Factor 1 (REGR)- General Lighting Quality	0.053	no	.1943946
		yes	-.3167912
Factor 2 (REGR)- Daylighting Quality	0.001	no	**.3485443**
		yes	-.5679981

As described in the methods, glare was measured via brightness contrast ratios between both the computer monitor and background and also between the overhead lights and the background. Ratios above 1:10 (target to background) were considered to be an indicator of glare, though mathematically the ratio was calculated as background to target, i.e. values above 10 are indicative of glare. Table 4-13 presents the ranges and means of glare measurements taken for the three measured lighting conditions, although lighting conditions were not adjusted in laboratories or cubicles.

Table 4-13. Descriptives of Glare Ratios Across Three Lighting Conditions

Condition	**N**	**N with glare present**	**Min**	**Max**	**Mean**	**St. Dev.**
"As Is" monitor/target to background	75	22	.7	49.5	7.7	7.9
"As Is" monitor to 1st electric light	57	39	1.6	401.4	67.2	89.5
"As Is" monitor to 2nd electric light	13	11	5.5	98.0	35.4	30.6
"Lights Off, Shades Open" monitor/target to background	44	17	.2	49.5	9.264	9.6221
"Lights Off, Shades Open" monitor to 1st electric light (*corridor light)	4	3	8.4	147.5	79.7	78.3
"Lights Off, Shades Open" monitor to 2nd electric light (*corridor light)	1	1	15.7	15.7	15.7	n/a
"Lights On, Shades Open" monitor/target to background	44	20	.8	55.5	10.4	9.7
"Lights On, Shades Open" monitor to 1st electric light	25	21	3.5	342.2	71.1	78.2
"Lights On, Shades Open" monitor to 2nd electric light	1	5	36.9	36.9	36.9	n/a

A univariate general linear model was conducted to evaluate the relationship between presence of glare in the “As Is” condition and the level of satisfaction with various attributes of the visual environment. No relationships were found to be significant with satisfaction levels. Next, two-way contingency analysis tables (cross tabulations of means) were conducted to evaluate whether presence of glare was statistically related to various sources of dissatisfaction or to the frequency of experienced dissatisfactions. Despite small sample sizes (n=4 for ‘no glare’ group) several relationships were revealed, all having to do with electric lighting rather than daylighting. Table 4-14 highlights the significant relationships between sources of dissatisfaction and glare presence that were found with their Pearson chi-square significance level. Interestingly, no attribute related to daylighting was found significant.

Table 4-14. Significant ($p < 0.10$) crosstabulation relationships between presence of glare and both problems and frequency of problems

Source of dissatisfaction	Lighting condition in which relationship statistically significant	Pearson chi-square Sig. (2-sided)
Too dark for paper-based-tasks	As Is	.017
Direct glare from electric light	As Is	.037
Frequency of reflections from electric lights on computer	As Is	.050
Frequency of electric light unevenly distributed	Lights On, Shades Open	.074
Frequency of reflections from electric lights on computer	Lights On, Shades Open	.074
Frequency of electric light too bright	Lights On, Shades Open	.090

The relationship between lighting controls and visual environment satisfaction was evaluated as well. As the only daylighting control provided to occupants are manual shades, statistical tests evaluated whether occupant perceptions of control over the shades related to any of the various attributes of the visual environment. It was found that occupants who felt they had control over the shades (n=56) rated "satisfaction with the amount of light" on average 6.14 while those without control (n=19) rated 5.05 on average (sig .092).

With regards to electric light control, occupants who reported having overhead light control (n=62) rated 5.6 for satisfaction with the amount of control over electric light, compared to those without control 4.5 (n=13) (sig .024). Additionally, occupants who reported having control over a task light (n=33), rated 5.94 for satisfaction with amount of light for computer compared to 5.14 for those who did not report a task light (n=42) (sig .038). Table 4-15 and Figures 4-18 through 4-20 summarize these findings on lighting controls.

Table 4-15. Significant ($p < 0.10$) Findings on Lighting Controls

	Significance		Means
		Control over shades:	
Satisfaction with amount of light	.092	Yes	**6.14**
		No	5.05
		Control over overhead light:	
Satisfaction with amount of control over electric light	.024	Yes	**5.6**
		No	4.5
		Control over task light:	
Satisfaction with amount of light for computer work	.038	Yes	**5.94**
		No	5.14

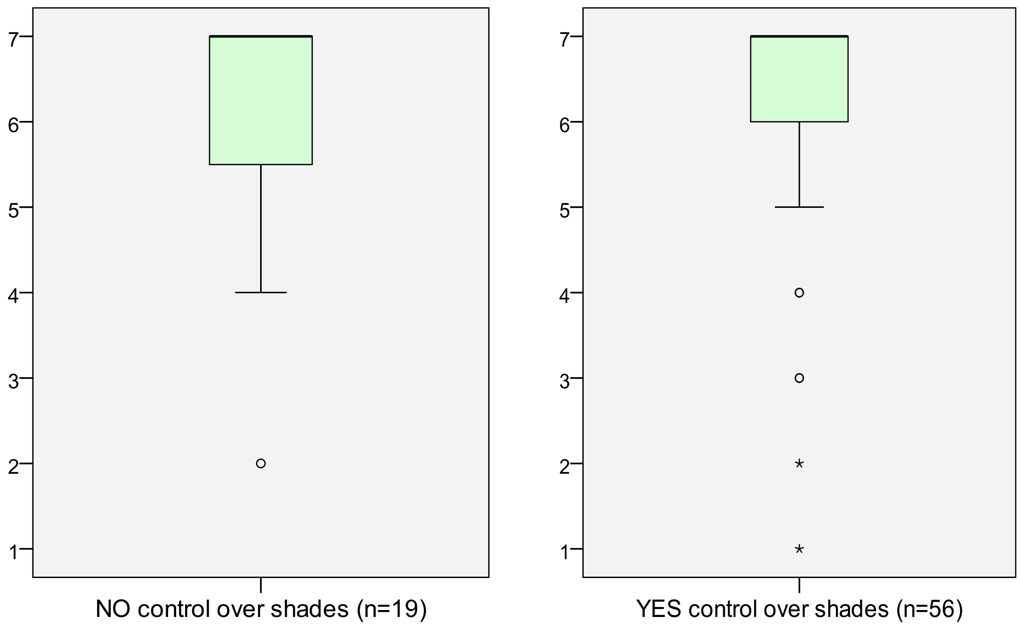

Figure 4-18. Satisfaction with the amount of light for control over shades

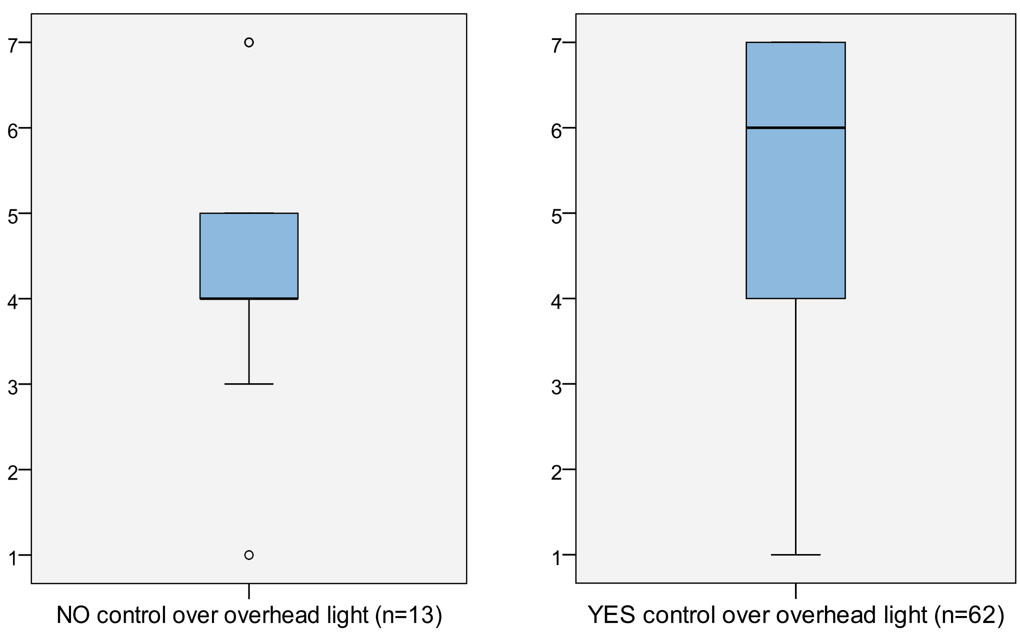

Figure 4-19. Satisfaction with the amount of control over electric light for control over overhead light

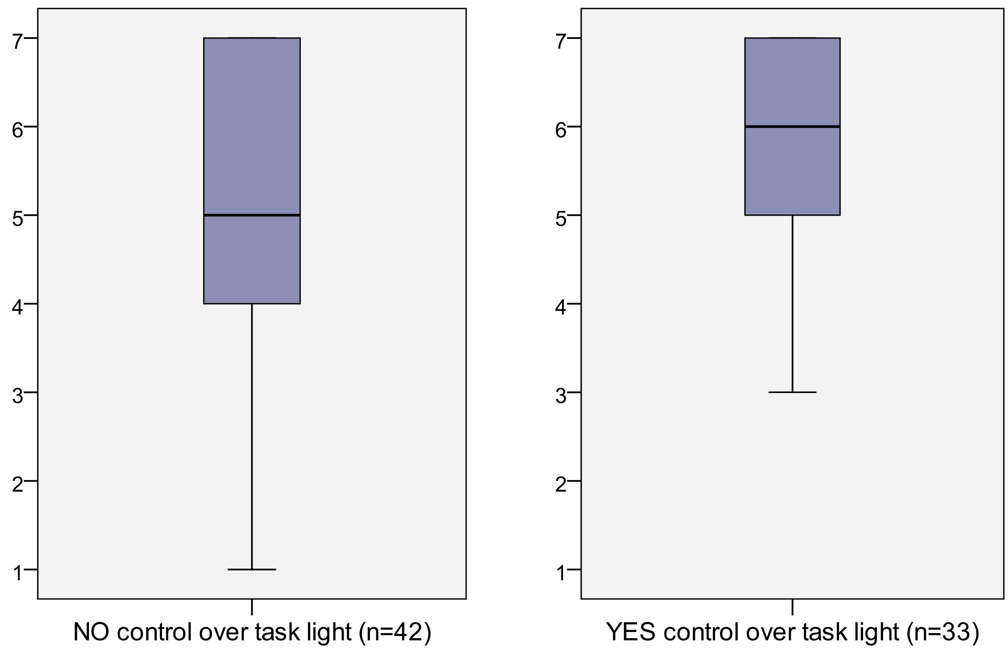

Figure 4-20. Satisfaction with the amount of light for computer work for control over task light

4.6 Physical Environment

Illuminance levels were measured in each workspace and recorded across all the lighting conditions. Figure 4-21 presents a scatterplot of these measurements. Statistical tests were run with satisfaction, comfort, and perceived performance levels both including and excluding the lighting outliers, but no findings were significant.

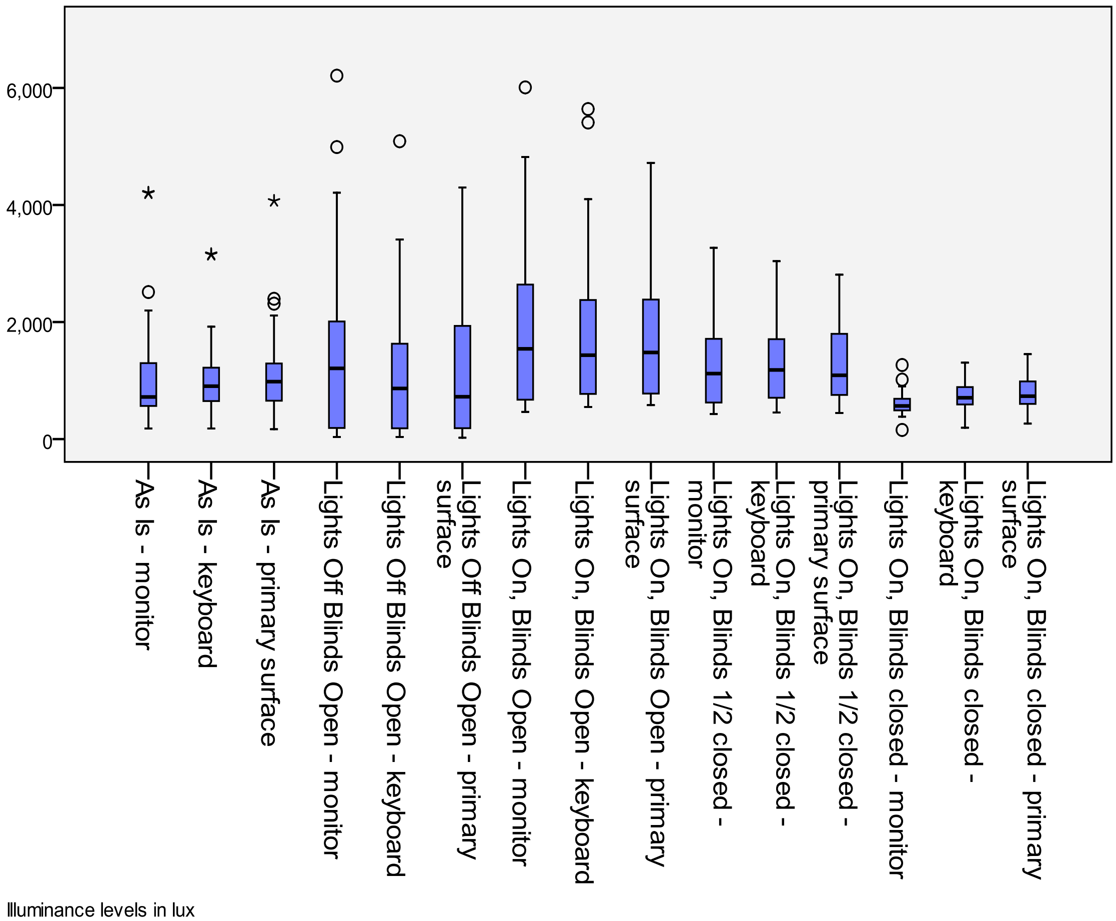

Figure 4-21. Scatterplot of Illuminance Levels in Workspaces Throughout All Five Lighting Conditions

As demonstrated in the scatterplot a large percentage of the workspaces are considerably bright with average light levels above 1000 lux and sometimes above 1500 lux. These bright conditions are indicative of an "over-lit" problem in Weill Hall especially for computer-based work which requires less than 500 lux for optimum comfort.

Figures 4-22 and 4-23 show light levels in vacant workspaces in the days following the field study. Since the workspaces were vacant, the light levels recorded are from daylight only. The graph reports the light levels between normal daylight hours. The different colored lines represent the position of the loggers with respect to the window as the days went on the logger was moved further from the window.

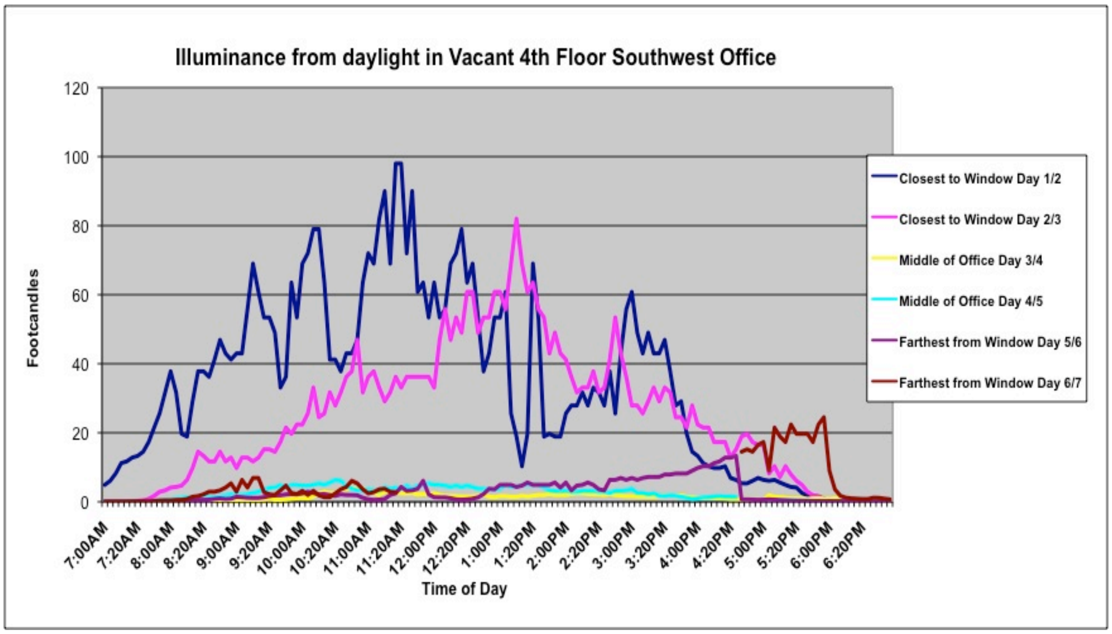

Figure 4-22. Illuminance from daylight in Vacant 4th Floor Southwest Office

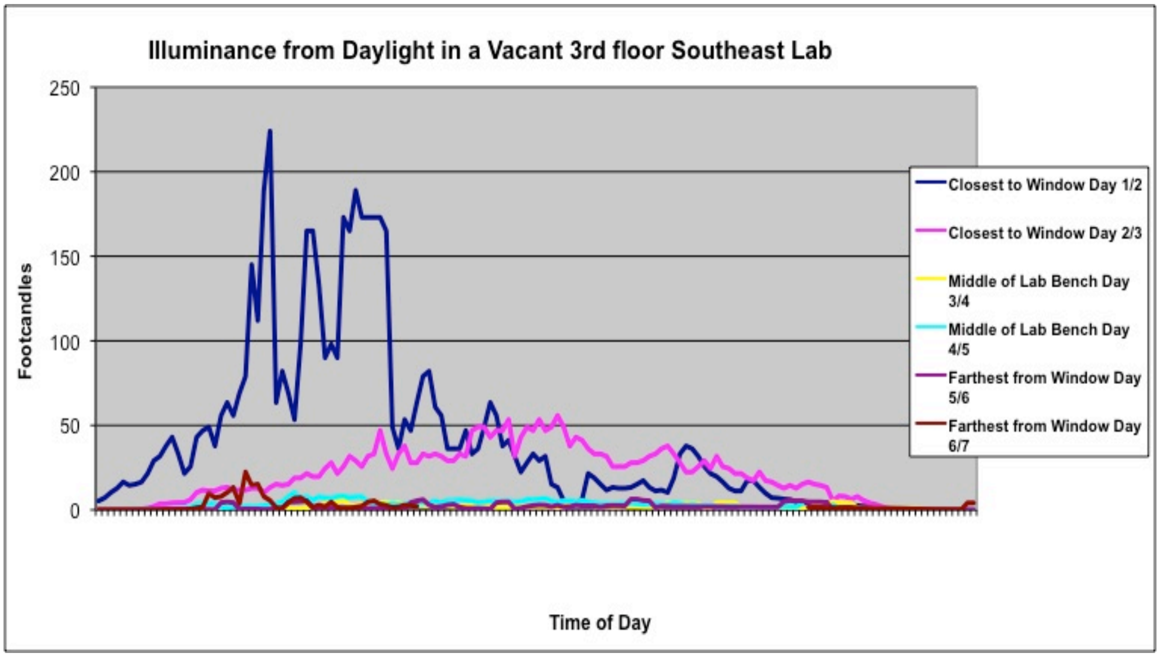

Figure 4-23. Illuminance from Daylight in a Vacant 3rd floor Southeast Lab

4.7 Follow-up Interview Findings

Finally, follow-up interviews in April revealed a few adaptive control behaviors by occupants seeking to improve their visual environment. In overcast weather when daylight is at a minimum, several occupants reported that the overhead light was not sufficient in providing light for their task and therefore brought in their own task light with maneuverable arm. One occupant specifically cited not having enough light at this desk for reading books.

For some occupants, enjoyment of the natural light is limited to the times of day when they are not receiving direct sun. Several interviewed occupants on the west side of the building have had to struggle in the afternoons. A few occupants reported making a habit of lowering their roller shades each afternoon in order to prevent veiling reflections on their computer screens. One professor on the first floor west side in particular found the glare so problematic that he resorted to always leaving the shades down. Additionally he moved his computer off of the desk and onto the credenza behind his desk against the window. Another occupant on the west side reported needing to take planned breaks in his desk work during the same hour on sunny afternoons because the veiling reflections on his computer monitor were too severe to work around even with the shades closed.

The interviews however showed, that overall, the light in Weill Hall is still positively received. The facility manager reported having received no complaints regarding the lighting and several professors commented that they feel their labs in Weill Hall are much more productive their in previous facilities, citing the natural light as making the difference.

Lastly, the occupants who were interviewed provided several suggestions for possible performance indicators to use in lab settings in future research. The suggestions include: measuring efficiency and how much one accomplishes in a single day, measuring the amount of 'lost time,' measuring the ease and speed of deciphering data or identifying changes materializing in a test tube, measuring the speed of taking graduated cylinder measurements, and measuring the number of times an experiment must be started over.

CHAPTER 5

DISCUSSION

5.1 Conclusions

The aim of this study was to first investigate if access to daylight had an impact on occupant comfort, satisfaction, and perceived performance and to then look for specific characteristics of the daylighting strategy associated with these occupant perceptions. The data from this study suggests that occupants in daylit spaces are more satisfied with their work environment, although conclusions regarding perceived performance cannot be made. Exterior horizontal shading was found to have the strongest association to higher comfort and satisfaction ratings. Small scale fixed exterior vertical shading was actually found to have a negative correlation to occupant comfort and satisfaction, although this may be due to this specific vertical shading design.

As shown in Figure 4-4, windowed workspaces are associated with significantly greater ratings by occupants of the work environments. Additionally as Figure 4-2 demonstrates, occupants overall are highly satisfied with their workspaces in Weill Hall, which is without a doubt an abundantly daylit facility. Looking specifically at daylighting design characteristics, occupants who work in spaces where horizontal shading is present as Table 4-7 shows are on average more satisfied and more comfortable than occupants in workspaces without horizontal shading.

Findings on window orientation and shape of fin are slightly less decisive, but, as Table 4-10 shows, are still significant showing that when occupants' windows face east or have a triangular fin they report higher satisfaction levels with the daylighting attributes of their workspaces. Interestingly, those participants whose windows faced east were the same participants having triangular vertical shading fins. Furthermore, those same participants also enjoyed a reasonably different view than the participants who faced west and who had rectangular-shaped vertical shading. To the east of Weill Hell are lush green athletic fields, while to the immediate west is another laboratory building that shields a percentage of office occupants from campus views. It therefore becomes intriguing to discover that those facing east agreed more strongly that daylighting in their workspace supports their work as this lends support to the idea that quality of view matters. It should again be noted that the difference in window orientation (and shape of fin too) follows the same dichotomy between office and lab spaces as labs are present on the east façade (where triangular fins are) and offices are present on the west façade (where rectangular fins are) thus presenting a possible confounding variable. Still, statistical tests run on workspace type as a design feature (office vs. lab, as cubicles were excluded due to insufficient sample size) and satisfaction levels did not yield any significant relationships though through interviews it was found that occupants appreciate the daylight in the laboratory spaces and incredible deal.

Looking at vertical shading of any shape, as Table 4-9 demonstrates, it was found that the presence of small scale fixed exterior vertical shading had a negative correlation to occupant satisfaction levels. This finding falls contrary to the common recommendations regarding vertical shading (Ander, 2003). One reason for this counter-intuitive finding is possibly the size of the projection of the vertical shading on the building. The vertical shading, present on the east and west façades, measures only one and a half feet deep. It is quite possible that given the sun angle at the time of year of the survey and this relatively shallow depth, there would be little expected benefit from the vertical shading.

Taking a more explorative stance with the data, further conclusions with regards to glare and lighting controls are also forthright. As reported in the results chapter, no statistical relationships between a measured presence of glare (contrast ratio greater than 1:10) and self-reported satisfaction levels with glare-related attributes were found to be significant in any of the lighting conditions. However, as reported in Figure 4.17, 11 out of the 30 occupants who reported dissatisfaction with at least one visual feature cited veiling reflections from daylight as a reason. Furthermore, when sources of dissatisfaction were examined against the measured presence of glare no link between any daylighting related problems and the presence of glare was found. However, as Table 4-14 demonstrates, relationships between the presence of glare from electric sources and the reporting of problems with glare from electric sources and the frequency of such problems were found to be significant. This would suggest that while occupants may be unaware of glare when it originates from daylight, they are more cognizant and irritated when the glare comes from electric light. This seemingly higher tolerance for glare from daylighting supports similar previous conclusions from Hopkinson (1970) and Osterhaus (2001) who maintain that with windows the added bonus of a view can negate undesirable consequences like glare. Indeed, participants in Weill Hall generally do have views of a large suburban campus with well-maintained green athletic fields adjacent.

With regards to lighting controls, it was found that occupants who had control over window shades, were on average more satisfied with the amount of light in their workspace than those occupants without shade control. Additionally, occupants with control over the electric lighting, especially those with a task light, reported higher levels of satisfaction with the *amount* of light at their computer workstations. While at first this link might not seem apparent, re-consideration of prior research confirms the link between the two: controls and amount of lighting. As DiLouie (2004) writes, "Personal control bridges the gap between a building design that attempts to satisfy the majority and people who have very different needs based on a range of factors." This especially applies in larger rooms and shared workspaces where larger controls for overhead lights and window shades are shared. More over, it has been argued that task lighting has the most to do with productivity over all other types of lighting because different tasks require different amounts of minimum lighting and task lights provide for this personalized need and can therefore result in greater satisfaction (Abdou, 1997).

5.2 Limitations to Research

One of the largest limitations to this study is the sample size. Small samples prohibited many tests from being conducted. While 75 participants may be quite representative of Weill Hall, the sample became smaller and smaller as it was broken down into conditions (e.g. glare sources, seat distance from window, workspace type, etc.) and thus the statistical tests lost validity and many comparisons and relationships could not be examined. Most importantly lost was the ability to run tests on windowed versus windowless environments with an 'n' as large as only seven and sometimes as small as four. Additionally, this study only examined the design aspects of a single building during a single season, and so regardless of the sample size the findings should be generalized with care.

Another limitation to the research relates to the use of a lumen meter for spot measurements, which was a key tool in the daylighting design evaluation toolkit. As several correlation tests linked survey responses to these light readings, the possibility that these readings might not have been representative of the brief ten-minute period I had hoped to capture should be noted. It cannot be known whether the daylighting was under or over-stated, if at all, and so alternative conclusions cannot be hypothesized.

Similarly, it is also difficult to know if participants heeded the direction to only consider the lighting conditions in their workspace during the time of survey. While my toolkit only allowed me to take spot measurements, occupants had several months of experience and opinions about their workspace that may have been difficult to disregard. Correlations between survey responses and the spot light levels were found un-significant and this may be a possible reason why.

Finally, social desirability is always a threat with self-report surveys and could have been a factor in participants' answers. As occupants of one of the newest buildings on campus, something seen traditionally as a privilege, participants may have been hesitant to express dissatisfaction with any of the building's lighting qualities. Along similar lines, hypothesis guessing may have lowered the construct validity of the survey as occupants could have gathered that daylighting was the study's main focus, and not the entire visual environment as the survey was titled, and this could have influenced their survey answers.

5.3 Recommendations for future study

For a future study I recommend examining multiple seasons to discover a year-round picture of the usefulness of daylighting. The field study was conducted in February, a winter month when there is generally a good amount of cloud cover, prohibiting field study testing on several days. Field study testing in the summer season when the solar radiation intensity is greater and the sun angle higher, might reveal new relationships between daylighting and occupant comfort, satisfaction and performance as well as other problems with glare. However, testing effects or reactivity may become a threat if occupants become too familiar with the survey. An alternative to multi-season testing might be to wait until the building was more than one year old so that occupants could become more expert on their workspace and then relate or explain any seasonal differences that they themselves became aware of over the course of a year. Also, allowing a longer period of time to pass between occupancy and testing can also reduce the chances of 'newness' having an impact on the study.

Findings regarding daylighting's effects on performance could not be made which was not too surprising given the assessment measure for performance. Future research that aims to assess performance or productivity in a laboratory environment should be prudent in the selection of a performance indicator that is both appropriate to the type of lab work and functionally and objectively measurable. Follow-up interviews after the field study enabled me to inquire about better performance indicators to use in a laboratory setting, but lab users struggled to identify a generally applicable measure, thereby confirming the limitation. For more meaningful results, future research should tailor performance indicators to be experiment-specific even though this may not allow for wide comparisons of data.

Another way to strengthen this study would be to use an experimental research design in conjunction with the daylighting design evaluation toolkit. An ideal opportunity for such an experiment could be a non-daylit laboratory where half of the occupants would be re-locating to a daylit building while the other occupants remain, therefore serving as a control. Conducting a pre-move survey, if possible, would be valuable to establish a picture of the pre-move "without daylighting" condition. An opportunity where identical research is occurring in both daylit and non-daylit laboratories provides the added advantage of being able to more easily compare productivity indicators.

In future research on glare and visual comfort it would also be interesting to examine the relationship between window position and monitor positioning and visual comfort. Data regarding the variable of monitor position with respect to window location was not collected in my study and therefore it's very likely that a critical factor of visual comfort was overlooked.

Lastly, to combat the risk of occupants not heeding the direction to consider only the current lighting conditions at the time of their survey, the study could be re-designed to ask about long-term satisfaction in their workspace. In addition, the altered surveys could be tied to long-term lighting data taken from the workspaces perhaps with loggers or time-lapse cameras. Computer simulations can also aid the understanding of the effects of different daylighting strategies across different seasons and climates.

APPENDIX A: Occupant Survey

Weill Hall Work Environment Survey

This survey aims to identify the relationship between the visual work environment and the satisfaction of workplace occupants. Your answers are completely confidential.

I. Personal Description

1. Gender:
- ☐ Female
- ☐ Male

2. How many hours do you work in Weill Hall per week? _______ hours

3. When did you move in?
- ☐ January or February 2009
- ☐ November or December 2008
- ☐ September or October 2008
- ☐ July or August 2008
- ☐ May or June 2008

4. Where did you work before?
- ☐ On campus: Building:______________________ Room #:_________________
- ☐ Off Cornell's campus (another university)

5. Was there a window in your previous office? (Circle one) Yes No

6. How would you describe your position in Weill Hall?
- ☐ Faculty
- ☐ Post Doc
- ☐ Graduate student
- ☐ Undergraduate student
- ☐ Research staff
- ☐ Admin/Support
- ☐ Technician
- ☐ Management
- ☐ Other. Please specify _____________________

7. Do you have more than one workspace in Weill Hall? (i.e. an office AND a laboratory)
- ☐ Yes
- ☐ No

8. What is your age?
- ☐ Under 21 years
- ☐ 21 to 30 years
- ☐ 31 to 40 years
- ☐ 41 to 50 years
- ☐ 51 to 60 years
- ☐ 61 to 70 years
- ☐ Over 70 years

II. Nature of Work

9. In a TYPICAL WORK WEEK, what percentage of your time do you spend at the following places?
*****Should add to 100%*****

At my desk in a private/shared office	________%
In a lab space	________%
In meetings (away from my desk or lab)	________%
In other shared spaces (lounges, cafeterias)	________%

10. When working at your desk within your private/shared office, for a typical work week, what percentage of your time is spent on the following tasks? ***Should add to 100%*   [Skip if you do not have an office]**

Getting organized	_________%
Phone interaction	_________%
Email processing	_________%
Reading on the computer	_________%
Reading paper-based materials	_________%
Writing	_________%
Planned meetings	_________%
Casual meetings or conversations with coworkers	_________%
Other	_________% Please specify ____________________

11. When working at your lab, for a typical work week, what percentage of your time is spent on the following tasks? ***Should add to 100%*   [Skip if you do not have a lab]**

Getting organized	_________%
Lab work	_________%
Reading on the computer	_________%
Reading paper-based materials	_________%
Writing on computer (entering data, writing report, etc.)	_________%
Writing on paper (entering data, taking notes, etc.)	_________%
Discussion/Conversation	_________%
Other	_________% Please specify _____________________

12. How satisfied would you say you are with your job?

Least satisfied			most satisfied
1	2	3	4

Directions: For the remainder of the survey please answer according to your experience in the WORKSPACE YOU ARE IN AT THIS MOMENT.

13. How frequently do you experience the following feelings at work in THE SPACE YOU ARE IN AT THIS MOMENT?

	Always	**Daily**	**Several times/week**	**Seldom**	**Never**
Feeling excited about work	☐	☐	☐	☐	☐
Being in good spirit	☐	☐	☐	☐	☐
Feeling disorganized	☐	☐	☐	☐	☐
Looking forward to working in Weill Hall	☐	☐	☐	☐	☐

III. Individual Workstation or Lab

14. What type of lighting is provided in THE SPACE YOU ARE IN AT THIS MOMENT? (PLEASE CHECK ALL THAT APPLY)

- ○ Overhead light
- ○ Desk lamp with fixed arm
- ○ Desk lamp with adjustable arm
- ○ Under-cabinet light

15. Which of the following CONTROLS do you have over the lighting in THE SPACE YOU ARE IN AT THIS MOMENT? (PLEASE CHECK ALL THAT APPLY)

- ○ Light switch for ceiling lights
- ○ Dimmer switch for ceiling lights
- ○ Window blinds or shades
- ○ Desk/task light
- ○ Other. Please specify________________________________
- ○ None of the above

16. How satisfied are you with the following factors?
(PLEASE ANSWER IN REGARD TO THE SPACE YOU ARE IN AT THIS MOMENT)

	Very dissatisfied			Neutral			Very satisfied
Amount of light in this space	☐	☐	☐	☐	☐	☐	☐
Distribution of light in this space	☐	☐	☐	☐	☐	☐	☐
Amount of daylight in this space	☐	☐	☐	☐	☐	☐	☐
Distribution of daylight in this space	☐	☐	☐	☐	☐	☐	☐
Visual comfort of the electric lighting (e.g. glare, reflections, contrast)	☐	☐	☐	☐	☐	☐	☐
Visual comfort of the daylighting (e.g. glare, reflections, contrast)	☐	☐	☐	☐	☐	☐	☐
Amount of control you have over the electric lighting	☐	☐	☐	☐	☐	☐	☐
Amount of control you have over the daylighting	☐	☐	☐	☐	☐	☐	☐
Amount of light on desk for paper-based tasks (e.g. reading & writing)	☐	☐	☐	☐	☐	☐	☐
Amount of light for computer work	☐	☐	☐	☐	☐	☐	☐
Quality of lighting in your work area in general	☐	☐	☐	☐	☐	☐	☐

17. Overall, how satisfied are you with the visual environment in THE SPACE YOU ARE IN AT THIS MOMENT?

Very dissatisfied			Neutral			Very satisfied
☐	☐	☐	☐	☐	☐	☐

18. Overall, does the visual environment in THE SPACE YOU ARE IN AT THIS MOMENT support or interfere with your ability to get your job done?

Interferes			Neutral			Supports
☐	☐	☐	☐	☐	☐	☐

19. Does the -DAYLIGHTING in THE SPACE YOU ARE IN AT THIS MOMENT support or interfere with your ability to get your job done?

Interferes			Neutral			Supports
☐	☐	☐	☐	☐	☐	☐

20. While working in THIS SPACE during an average week, I make FEWER technical errors than I did in my PREVIOUS WORKSPACE BEFORE moving.

Strongly disagree			Neutral			Strongly agree
☐	☐	☐	☐	☐	☐	☐

If you have answered WORSE THAN NEUTRAL for the previous questions 13-16, please continue with the survey. If all of your answers were rated BETTER THAN NEUTRAL then you are finished. Thank you!

21. Please check the boxes below describing what factor(s) contribute(s) to your dissatisfaction in THE SPACE YOU ARE IN AT THIS MOMENT. (PLEASE CHECK ALL THAT APPLY)

- ○ Too dark even with all the lights on
- ○ Too bright even with all the lights off
- ○ Not enough daylight
- ○ Too much daylight
- ○ Not enough electric lighting
- ○ Too much electric lighting
- ○ Too dark for paper-based work
- ○ Too bright for computer work
- ○ Electric lighting flickers
- ○ Electric lighting has an undesirable color
- ○ Direct glare for daylight
- ○ Reflections from daylight on computer screen
- ○ Direct glare from electric light fixture(s)
- ○ Reflections from electric light on computer screen
- ○ Shadows on the work surface
- ○ No control over daylight/sunlight
- ○ No task lighting
- ○ Task lighting not relocatable
- ○ Overhead light not where I need it
- ○ Blinds or windowshades hard to operate
- ○ Other please specify: ____

22. How FREQUENTLY do you experience the following environmental conditions in THE SPACE YOU ARE IN AT THIS MOMENT?

	Always	Daily	Several times/week	Seldom	Never
Too much daylight	☐	☐	☐	☐	☐
No daylight	☐	☐	☐	☐	☐
Direct glare for daylight	☐	☐	☐	☐	☐
Reflections from daylight on computer screen	☐	☐	☐	☐	☐
Electric light too bright	☐	☐	☐	☐	☐
Electric light too dim	☐	☐	☐	☐	☐
Electric light unevenly distributed	☐	☐	☐	☐	☐
Direct glare from electric light fixture(s)	☐	☐	☐	☐	☐
Reflections from electric light on computer screen	☐	☐	☐	☐	☐
Electric light flickers	☐	☐	☐	☐	☐
Undesirable color from electric light	☐	☐	☐	☐	☐

23. At what TIME OF DAY do you experience the following environmental conditions in THE SPACE YOU ARE IN AT THIS MOMENT?

	Morning	Noon	Afternoon	Never
Too much daylight	☐	☐	☐	☐
No daylight	☐	☐	☐	☐
Direct glare for daylight	☐	☐	☐	☐
Reflections from daylight on computer screen	☐	☐	☐	☐
Electric light too bright	☐	☐	☐	☐
Electric light too dim	☐	☐	☐	☐
Electric light unevenly distributed	☐	☐	☐	☐
Direct glare from electric light fixture(s)	☐	☐	☐	☐
Reflections from electric light on computer screen	☐	☐	☐	☐
Electric light flickers	☐	☐	☐	☐

24. How frequently do you experience the following problems in THE SPACE YOU ARE IN AT THIS MOMENT?

	Always	Daily	Several times/week	Seldom	Never
Unusual fatigue	☐	☐	☐	☐	☐
Sleepiness	☐	☐	☐	☐	☐
Feelings of stress	☐	☐	☐	☐	☐
Irritability	☐	☐	☐	☐	☐
Headaches	☐	☐	☐	☐	☐
Tired or strained eyes	☐	☐	☐	☐	☐
Dry, itching or irritated eyes	☐	☐	☐	☐	☐

The survey is complete. Thank you very much for your participation!

APPENDIX B: Pre-survey Checklist

Pre-Survey Administration Checklist

(this records the "AS IS" condition- very important to be accurate!)

1) Put sticker (coded) in box
2) Mark time of day ________________AM / PM
   MON TUE WED THU FRI
3) Weather condition (look outside):

   Full sun partly cloudy very cloudy but still just bright enough
4) What task are they working on now/when you interrupted?

   Paper based work (reading/writing) Computer work (reading/typing) Phone/conversation

   Lab paper based work Lab hands-on work
5) **Remind Person A to** Take photo on normal digital camera (capture furniture, blinds, etc)

******(If Cubicle or lab SKIP questions 6 - 8)***

6) Circle the shade/blinds position:

   Fully open 1/3 closed ½ closed 2/3 closed Fully closed
7) Circle the overhead lighting conditions: [need to confirm these options beforehand]

   both overhead lights on only main light on only perimeter light on all overhead lights off
8) Circle underbin lighting usage: underbin lights on underbin lights off
9) Based on these settings determine **which, if any, lighting condition should be skipped?**
   ______Lights off, blinds fully open
   ______Lights on, blinds fully open
   ______Lights on, blinds 50% closed
   ______Lights on, blinds 100% closed
10) **Ask:** are the "lighting conditions" in your space right now typical of how you have them at this time of day?
    Yes No

    If No: how are they usually? ____
11) **Ask:** what is your primary work surface for non-computer work?
    Record it here: ____
12) Any things to note (furniture, etc?: ____

    ____
13) ASK TO PLEASE TURN OFF COMPUTER MONITOR

BIBLIOGRAPHY

Abbaszadeh, S., Zagreus, L., Lehrer, D., & Huizenga, C. (2006) Occupant Satisfaction with Indoor Environmental Quality in Green Buildings. *Proceedings of Healthy Buildings 2006*, Lisbon, Vol. III, 365-370.

Abdou, O. A. (1997). Effects of Luminous Environment on Worker Productivity in Building Spaces. *Journal of Architectural Engineering*, 3(3), 124-132.

Allen, R. (1982). Pennsylvania Power and Light: a lighting case study. *Buildings*, 76(Mar.), 49-56.

Ander, G.D. (2003). *Daylighting Performance and Design,* 2nd Ed. Hoboken, NJ: John Wiley & Sons.

Baker, N. & Steemers, K. (2002). *Daylight Design of Buildings*. London, UK: James and James.

Barnaby, J.F. (1980). Lighting for Productive Gains. *Lighting Design and Application*, 10, 20-28.

Bayer, C.W., Bradley, J.S., Earthman, G.I., Eggleston, P.A., Fisette, P., Hall, C.B., Henry, G.T., Loftness, V.E., Mitchell, C.S., Rea, M.S., Sanoff, H., Spengler, J.D., Weiss, C.H., & Wilson, S.M. (2006). Review and Assessment of the Health and Productivity Benefits of Green Schools: An Interim Report. National Research Council of the National Academies. Retrieved April 12, 2009 from http://www.nap.edu/catalog.php?record_id=11574

BetterBricks. (2009). Which Glass Should I Use? Sorting it All Out. Retrieved June 1, 2009 from http://betterbricks.com/DetailPage.aspx?ID=808

Boubekri, M. & Boyer, L.L. (1992). Effect of Window Size and Sunlight Presence on Glare. *Lighting Research and Technology*, 2 (2), 69-74.

Boyce, P.R. (1973). Age, illuminance, visual performance, and preference. *Lighting Research and Technology*, 5(3), 125-144.

Boyce, P. R. (1995). "Illuminance selection based on visual performance - and other fairy stories." Paper presented at the Illuminating Engineering Society Annual Conference, New York, N.Y.

Boyce, P. (2003). "Human Factors in Lighting." Troy, NY: Lighting Research Center.

Cakir, A., Hart, D.J., & Stewart, T.F.M. (1980). *Visual display terminals: a manual covering ergonomics, workplace design, health and safety, task organization*. New York: Wiley.

Cheung, H.D., Chung, T.M. (2008) A study on subjective preference to daylit residential indoor environment using conjoint analysis. *Building and Environment*. 43(12), 2101–2111.

Christoffersen, J., Johnsen, K., Petersen, E., Valbjorn, O., & Hygge, S. (2000). Windows and Daylight – A post-occupancy evaluation of Danish offices. *Proceedings of the CIBSE/ILE Joint Conference University of York*, UK:CIBSE, p. 112–120.

Collins, B.L. (1975). *Windows and people: A literature survey, psychological reactions to environments with and without windows*. Department of Commerce, National Bureau of Standards, Building Science Series, 70.

Cuttle, K. (1983). People and windows in workplaces. *Proceedings of the People and Physical Environment Research Conference*. Wellington, New Zealand, 203-212.

Demos, G.D., Davis, S., & Zuwaylif, F.E. (1967). Controlled Physical Environments. *Building Research*, 4, 60-62.

DiLouie, C. (2004) Personal Control: Boosting Productivity, Energy Savings. *Lighting Controls Association*. Accessed August 22, 2009 from http://www.aboutlightingcontrols.org/education/papers/personalcontrol.shtml

Edwards, L. & Torcellini, P. (2002). A Literature Review of the Effects of Natural Light on Building Occupants. National Renewable Energy Laboratory. NREL/TP-550-30769.

Finnegan, M.C., Solomon, L.Z. (1981). Work Attitudes in Windowed Versus Windowless Environments. *Journal of Social Psychology*, 115, 291–292.

Fisk, W. J. (2000). Health and Productivity Gains from Better Indoor Environments and their Relationship with Building Energy Efficiency. *Annual Review of Energy and the Environment*. 25, 537-566.

Galasiu, A.D. & Veitch, J.A. (2006). Occupant preferences and satisfaction with the luminous environment and control system in daylit offices: a literature review. *Energy and Buildings*, 38, 728–742.

Good, N. (1999, July 16). Shedding Light on Productivity. *Portland Business Journal*, 16(21), p. 21.

Heerwagen, J. H., & Heerwagen, D. R. (1986). Lighting and psychological comfort. *Lighting Design and Applications*, 16(4), 47-51.

Heerwagen, J. H. & Zagreus, L. (2005). *The Human Factors of Sustainable Building Design: Post Occupancy Evaluation of the Philip Merrill Environmental Center*. Center for the Built Environment: University of California, Berkeley. Retrieved October 15, 2008, from http://repositories.cdlib.org/cedr/cbe/ieq/SR_CBF_2005/

Heschong, L. (2002). Daylighting and Human Performance. *ASHRAE Journal*, 44(66), 65-67.

Heschong Mahone Group. (1999a). Skylighting and Retail Sales: An Investigation into the Relationship Between Daylighting and Human Performance, Pacific Gas and Electric Company: Sacramento, CA.

Heschong Mahone Group. (1999b). Daylighting in Schools: An Investigation into the Relationship Between Daylighting and Human Performance, Pacific Gas and Electric Company: Sacramento, CA.

Heschong Mahone Group. (2001). Re-Analysis Report, Daylighting in Schools, for the California Energy Commission, published by New Buildings Institute, www.newbuildings.org

Heschong Mahone Group. (2003a). Windows and Offices: A Study of Worker Performance and the Indoor Environment (Technical Report), for the California Energy Commission.

Heschong Mahone Group. (2003b). Daylight and Retail Sales (Technical Report), for the California Energy Commission.

Heschong Mahone Group. (2003c). Windows and Classrooms: A Study of Student Performance and the Indoor Environment (Technical Report), for the California Energy Commission.

Hopkinson, R.G. (1970). Glare from windows. *Construction Research and Development Journal (CONRAD)*, 1, 98–105; 2, 169–175; 3 (1971) 23–28.

Hopkinson, R.G. (1972). Glare from daylighting in buildings. *Applied Ergonomics*, 3(4), 206-215.

Inui, M. & Miyata, T. (1973). Spaciousness in interiors. *Lighting Research and Technology*, 5(2), 103–111.

Inoue, T., Kawase, T., Ibamoto, T., Takakusa, S. & Matsuo, Y. (1988). The development of an optimal control system for window shading devices based on investigations in office buildings, *ASHRAE Transactions*, 94(2), 1034-1049.

Inoue, T. (2003). Solar shading and daylighting by means of autonomous responsive dimming glass: practical application. *Energy and Buildings*, 35(5), 463-471.

Kwok, A.G. & Grondzik, W.T. (2007). *The green studio handbook: environmental strategies for schematic design*. New York: Architectural Press.

Kroner, W., Stark-Martin, J.A., & Willemain, T. (1992). Rensselaer's West Bend Mutual Study: Using Advanced Office Technology to Increase Productivity. Troy, NY: Renssalaer Polytechnic Institute.

Küller, R., & Lindsten, C. (1992). Health and behavior of children in classrooms with and without windows. *Journal of Environmental Psychology*, 12, 305-317.

Lambert, G.W., Reid, C., Kaye, D.M., Jennings, G.L., & Esler, M.D. (2002). Effect of sunlight and season on serotonin turnover in the brain. *Lancet*, 360, 1840-1842.

Larson, C.T. (1965). *The effect of windowless classroom on elementary schoolchildren*. Architectural Research Laboratory, Department of Architecture, Ann Arbor, MI: University of Michigan.

Leaman, A. (1999). UK study links productivity to ventilation systems. *HPAC Magazine*, 71(11), 14.

Leather, P., Pyrgas, M., Beale, D., & Lawrence, C. (1998). Windows in the workplace: Sunlight, view, and occupational stress. *Environment and Behavior*, 30(6), 739–762.

Lee, E.S., DiBartolomeo, D.L., Vine, E.L., & Selkowitz, S.E. (1998). Integrated Performance of an Automated Venetian Blind/Electric Lighting System in a Full-Scale Private Office. Proceedings of the Thermal Performance of the Exterior Envelopes of Buildings VII, Clearwater Beach, FL.

Liberman, J. (1991). *Light Medicine of the Future*. New Mexico: Bear & Company Publishing.

Love, J.A. (1998). Manual switching patterns in private offices. *Lighting Research and Technology*, 30(1), 45–50.

McCormick, E.J. (1976). Human Factors in Engineering and Design. New York: McGraw-Hill.

MacLaughlin, J.A., Anderson, R.R., & Holick, M.F. (1982). Spectral Character of Sunlight Modulates Photosynthesis of Previtamin D_3 and its Photoisomers in Human Skin. *Science*, 216(4549), 1001-1003.

Manning, P. (1965). *Office Design: A study of environment*. Liverpool, England: Liverpool University Press.

Markus, T.A. (1967). "The Significance of Sunshine and View for Office Workers." *Proceedings of the CIE Conference on Sunlight in Buildings.* Rotterdam: Bouwcentrum International, p. 59-93.

Ne'eman, E. & Hopkinson, R.G. (1970). Critical minimum acceptable window size: a study of window design and provision of view, *Lighting Research and Technology*, 2(1), 17–27.

NEMA. (1989). "Lighting and human performance: a review." National Electrical Manufacturers Association, Washington, D.C.: Lighting Equipment Division.

Nicklas, M. & Bailey, G. (1997). Student Performance in Daylit Schools: Analysis of the Performance of Students in Daylit Schools. *Proceedings of the American Solar Energy Society*.

O'Connor, J., Lee, E., Rubinstein, F., Selkowitz, S. (1997). Tips for Daylighting with Windows: The Integrated Approach. Berkeley, CA: Ernest Orlando Lawrence Berkeley National Laboratory, LBNL-39945.

Osterhaus, W.K.E. (2001). Discomfort glare from daylight in computer offices: what do we really know? *Proceedings of the 9th European Lighting Conference, Lux Europa*. Reykjavik, Iceland: Illuminating Engineering Society, p. 448-456.

Osterhaus, W.K.E. (2005). Discomfort glare assessment and prevention for daylight applications in office environments. *Solar Energy*, 79(2), 140-158.

Paul, W. L. & Taylor, P.A. (2008). A comparison of occupant comfort and satisfaction between a green building and a conventional building. *Building and Environment*, 43(11), 1858-1870.

Phillips, D. (2004). *Daylighting: Natural Light in Architecture*. Burlington, MA: Architectural Press.

Pierson, J. (1995, December 17). Letting the Sun Shine In. *Wall Street Journal*. p. H1.

Rea, M.S. (1984). Window blind occlusion: a pilot study. *Building and Environment,* 19(2), 133–137.

Robbins, C. (1986). *Daylighting: design and analysis*. New York: Van Nostrand Reinhold.

Romm, J.J., (1999). *Cool Companies: How the Best Companies Boost Profits and Productivity by Cutting Greenhouse Gas Emissions*, Covelo, CA: Island Press.

Romm, J.J. & Browning, W.D. (1994) "Greening the Building and the Bottom Line: Increasing Productivity Through Energy-Efficient Design." Snowmass, CO: Rocky Mountain Institute.

Rubin, A.I., Collins, B.L., & Tibbott, R.L. (1978). Window blinds as potential energy saver – a case study, National Bureau of Standards, Building Science Series, 112, National Institute for Standards and Technology, Gaithersburg, MA.

Ruys, T., (1970). Windowless offices. M. Arch. Unpublished Master's Thesis. Seattle, WA: University of Washington.

Stenzel, A.G. (1962). Experience with 1000lx in a leather factory." Lichttechnik, 14,16.

Sundaram, S. & Croxton, R. (1998). Daylighting and Office Worker Productivity: A Case Study. *23rd National Passive Solar Conference*, Albuquerque, NM, p. 175–180.

Sundstrom, E.G. & Sundstrom, M.G. (1986). *Work Places: The Psychology of the Physical Environment in Offices and Factories*. New York, NY: Cambridge University Press.

Thompson, B. & Jonas, D. (2008). Workplace design and productivity: are they inextricably linked? *Property in the Economy*, Royal Institution of Chartered Surveyors. Accessed April 12, 2009 from www.rics.org

Veitch, J.A. (2001). Psychological Processes Influencing Lighting Quality. *Journal of the Illuminating Engineering Society*, 30(1), 124-140.

Veitch, J.A. & Gifford, R. (1996). Assessing Beliefs about Lighting Effects on Health, Performance, Mood, and Social Behavior. *Environment and Behavior*, 28: 446-470.

Vischer, J.C. (1989). *Environmental quality in offices*. New York, NY: Van Nostrand Reinhold.

Whole Building Design Guide. (2009). "Daylighting." Retrieved May 15, 2009 from http://www.wbdg.org/resources/daylighting.php

Wurtman, R. J. (1975). The Effects of Light on the Human Body. *Scientific American*. 233(1), 68–77.